Strategic Analyses of the National River Linking Project (NRLP) of India: Series 4

Water Productivity Improvements in Indian Agriculture: Potentials, Constraints and Prospects

M. Dinesh Kumar and Upali A. Amarasinghe, editors

IWMI
International Water Management Institute

CGIAR Challenge Program on WATER & FOOD

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IWMI receives its principal funding from 58 governments, private foundations, and international and regional organizations known as the Consultative Group on International Agricultural Research (CGIAR). Support is also given by the Governments of Ghana, Pakistan, South Africa, Sri Lanka and Thailand.

The editors: M. Dinesh Kumar, formerly Director IWMI-TATA Water Policy Program, presently Executive Director, Institute for Resource Analyses and Policy (IRAP), Hyderabad; Upali A. Amarasinghe, Senior Researcher, International Water Management Institute (IWMI), New Delhi Office.

Kumar, M. D.; Amarasinghe, U. A. (Eds.). 2009. *Strategic analyses of the National River Linking Project (NRLP) of India, series 4. Water productivity improvements in Indian agriculture: potentials, constraints and prospects*. Colombo, Sri Lanka: International Water Management Institute. 160p.

/ water productivity / cereals / irrigation water / water quality / water use / multiple use / water demand / agricultural production / crop yield / electricity supplies / food production / crop production / rainfed farming / irrigated farming / irrigation systems / cropping systems / farming systems / case studies / tube well irrigation / dairy production / milk production / economic aspects / supplemental irrigation / water deficit / water allocation / food security / policy / India /

ISBN: 978-92-9090-712-1

Cover photo by Dr. Alok Sikka (National Rain-fed Authority, NASC Complex, New Delhi, India) shows furrow-irrigated raised-bed-planted wheat.

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Acknowledgement

The project team greatly appreciates the assistance of Dr. Dinesh Kumar, formerly the Director IWMI-TATA Water Policy Program, and presently the Executive Director, Institute for Resource Analyses and Policy (IRAP), Hyderabad, in leading the research and synthesis for this volume. The project team, along with Dr. Kumar, would also like to thank the authors of different chapters for their timely and thoughtful contributions to the research on water productivity improvements reported in this volume.

The project team also appreciate the guidance of the project advisory committee - the Chairman, Prof. M. S. Swaminathan, and others, including Prof. Yoginder K. Alagh, Prof. Vijay S. Vyas, Prof. Kanchan Chopra, Prof. Vandana Shiva, Prof. Frank R. Rijsberman, Mr. Anil D. Mohile, Mr. S. Gopalakrishnan, Mr. Deep Joshi, Dr. Peter McCornick and Dr. Tushaar Shah.

The authors would also like to thank Drs. Hugh Turral, David J. Molden, Charlotte de Fraiture, Mark Giordano and Mobin-ud-din Ahmad of the International Water Management Institute; Dr. Petra Hellegers, Associate Professor of Economics at Wageningen University and Research Centre; and a team of scientists including Drs. A. Haris, A. Upadhyay, P. R. Bhatnagar, A. Dey, A. R. Reddy and A. K. Singh at the Indian Council of Agricultural Research (ICAR), Patna complex. Their assistance or comments on various stages of research and preparation of different manuscripts were immensely helpful.

The draft synthesis of the chapters/papers was presented at the National Workshop on ‘Strategic Issues of Indian Irrigation’ held on April 7-8, 2009 in New Delhi. The authors would like to thank Dr. A. Narayanamoorthy, Professor and Head, Centre for Rural Development, Alagappa University, Tamil Nadu, for his detailed comments on the book chapters/papers, and the participants of the workshop for their comments on the synthesis.

Finally, we express our thanks to Ms. Mala Ranawake for general coordination and logistical support; Mr. Joseph Perera, Mr. Nimal Attanayake and Ms. Pavithra Amunugama for managing the editorial, layout and production process, respectively, of this volume.

Project

Research in this book is part of the project no. 48, “Strategic Analysis of India’s National River-Linking Project (NRLP)” of the CGIAR Challenge Program on Water and Food (CPWF).
www.waterandfood.org

Partners

This research study is a collaboration of the following organizations.
National Rainfed Area Authority of India, New Delhi, India
Department of Agricultural Economics, Banaras Hindu University, Varanasi, India
Faculty of Environmental Sciences, Wageningen University and Research Centre, Wageningen, the Netherlands

Preface

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

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

This volume, the fourth in a series of publications, presents findings of research in Phase III. It assesses the potential contribution, constraints and prospects of contributions from water productivity improvements in the irrigation sector to an alternative water sector perspective plan for India.

Water Productivity Improvements in Indian Agriculture: Potentials, Constraints and Prospects

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Introduction

India is still an agrarian country, although the structure of the economy is gradually changing. Industrialization and urbanization setoff in the 1990s resulted in a greater contribution from the manufacturing and service sectors to the national economic output. Today, the agriculture sector contributes to only 17% of the gross domestic product (GDP), yet nearly 70 % of the country's population live in rural areas and a major part of this depends on agriculture-related economic activities for their livelihoods. Projections show that it would take another five decades before the population starts stabilizing (Visaria and Visaria 1997). Hence, sustaining agriculture production, particularly the production of food grains in tune with population growth and changing consumption patterns, is an important task. This task is not only essential for feeding the growing population for a large country like India, but also important for supporting livelihoods and reducing the poverty of India's large rural population[1] (Chaturvedi 2000). Moreover, water demand in nonagricultural sectors, including that for the environment is increasing and many regions in the country are facing severe water stress (Amarasinghe et al. 2005, 2008). Thus, efforts to manage water efficiently in the agriculture sector and produce more crop and value per drop are gaining momentum now more than ever before.

Agriculture continues to account for a major share of the water demand in India (Amarasinghe et al. 2008). South-west monsoon provides a major part of India's annual rainfall, and the quantum varies widely across space (GOI 1999). In most places, growing crops require an artificial provision of water during non-monsoon season and in some places even during the monsoon. In fact, only one-third of the agricultural production in the country comes from rain-fed areas, which account for two-thirds of the crop lands. As per official projections, a major share of the future growth in India's agriculture production would have to come from

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[1] Several studies in the past have indicated that agricultural growth, especially growth in food grain production positively impacted on reducing rural poverty (Hazzle and Haggblade 1991; Rao 1994; Ghosh 1996; Desai and Namboodri 1998). Rural poverty has correlated with relative food prices, which is affected by fluctuations in food supply (Ravallion 1998; Dev and Ajit 1998).

increasing cropping intensity, and bringing rain-fed areas under irrigated production, rather than expanding the net cultivated area (GOI 2002), all of which would require irrigation water.[2]

The extent of net additional irrigation at the aggregate level would depend heavily on three aspects. The first two aspects - the extent of growth needed in agriculture production, particularly production of food grains; and the extent to which we can increase the productivity of water use in agriculture are well recognized and researched. However, the third aspect, how and where those improvements in water productivity (WP) are going to occur are less recognized.

But, the last aspect on WP improvements is extremely important. It is a false notion that raising the production of a particular crop by a certain degree, by increasing WP, would compensate for the increase in future water demand for raising the production of a particular crop by the same degree. Several situations explain this false notion.

1. A region can get all its production from rain-fed crops. In such a case, it is quite possible that the productivity improvement comes from an increase in yield of crops in a rain-fed area, through supplementary irrigation. WP gains through supplementary irrigation would only help us take some of the rain-fed areas out of cultivation, thereby freeing some of the agricultural land for other uses. However, most of the water used up by rain-fed crops, i.e., soil moisture, in these rain-fed lands cannot be re-allocated to irrigate crops or for any other use. Thus, it will not reduce the need for diverted water.

2. The sum of the extent of water resource augmentation for irrigation in different regions could be more than the required net increase in irrigation water supply at the aggregate level. For instance, a region could have great scope for WP improvement through reduction in consumptive use of water for irrigation. But these regions may not have much additional land, such as Punjab or Haryana. Such gains in WP won't reduce the need for additional water supply in another region that has additional arable land to produce food. Nevertheless, it would only free up some of the water resources in the first region for reallocating to the environment or another sector of use.

3. If WP (kg/evapotranspiration) improvements can come from supplementary irrigation of rain-fed crops in one region, such as certain parts of central India or in the Godavari Basin in peninsular India, which has low levels of water resources development, then it would still require a lot of additional water. This additional water, however, can be at the expense of water availability of another region with fully developed water resources for intensive irrigation. The latter, by reducing its irrigated area or improving the productivity in its region by shifting to water-efficient non-food crops, part with its water for the benefit of the former region.

4. If reduced consumptive water use in irrigated crop production can improve WP, then this would lower the need for increased irrigation only if additional land is available for cultivation in the same area to achieve a greater crop output with the saved

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[2] However, this does not mean that growth in production from rain-fed areas is not possible without large irrigation infrastructure. Sharma et al. (2009) showed that small supplementary irrigation in critical periods of water stress can significantly increase productivity in rain-fed lands.

quantum of water. If the improvement comes from an increased use of fertilizers in certain regions, which also brings about crop yield improvements, then this would mean there would be a reduced need for augmenting irrigation.

All of the above-mentioned hypothetical situations actually exist in India. So, in the ultimate analysis, it would appear that the benefit of WP improvement cannot be fully translated into an equivalent reduction in the requirement for developing additional water resources, although significant reductions could still be possible. However, the outcomes of WP improvement would be multiple. It increases the stream flows in some areas; reduces pressure on groundwater in some other areas; boosts productivity and production and freeing up of rain-fed land in some other areas with a consequent increase in stream flows from the river catchments owing to change in land use hydrology. All these are important for the country. So improving WP in agriculture is an important component of a water sector perspective plan. A water perspective plan for water resources for India should indicate:

- how the demand for water is going to grow in different sectors, including environment, and in different regions;
- how much of the additional demand for water can be managed through improvements in WP in different competitive sectors of water use in different regions;
- what kind of interventions would be required for improving productivity of water use and at what scale (supplementary irrigation, controlled water allocation, micro- irrigation, conservation technologies etc.);
- how much of this gets translated into real reduction in irrigation water demands in every region where it matters, or does it actually increase water demand in some regions;
- what should be the increase in utilizable water supplies in different regions; and what should be the aggregate increase in water supplies, after considering – inter-regional re-allocation of the freed-up resource.

This book explores the potential interventions for WP improvement in Indian agriculture, the scale of adoption of these interventions and their potential impacts on future agricultural water demand.

The papers in this book are results of various research activities conducted in Phase III of the project on ‘Strategic Analysis of National River Linking Project’ (NRLP) of India (CPWF 2005). The Phase I and II of the NRLP project assessed: ‘India’s Water Futures: Scenarios and Issues’ (Amarasinghe et al. 2009) and ‘Social, Hydrological and Environmental Cost and Benefits of the River Linking Project’ (Amarasinghe et al. 2008), respectively. The Phase III studies explored various options to interlinking of rivers, which can contribute to an alternative water-sector perspective plan for India. As part of this, Saleth (2009) explored the potential, prospects and constraints for promoting demand management strategies in the Indian irrigation sector. The papers in this book assess potential, prospects and constraints for promoting WP improvements in the Indian agriculture sector. They provide fresh empirical analysis based on primary data across India on crop inputs and outputs and also district level secondary data on crop production, crop yields and agro-meteorology. It covers both rain-fed areas and irrigated areas. In addition to field crops, the analysis also included dairying under composite farming systems.

This book discusses various complex considerations involved in analyzing WP in agriculture in India that goes beyond the conventional 'crop per drop' paradigm. It further examines how integration of these considerations in assessing WP provides us with new opportunities or sometimes induces constraints in the traditionally known approaches for enhancing WP in agriculture. It discusses various improvement measures of WP in both rain-fed areas and irrigated areas, not only at the field level, but also at the farm level and regional/basin level. It also specifies the regions where these measures would work, by using empirical evidences from various locations in India. But, while doing this, it also analyzes the macro-level constraints induced by physical, technological and infrastructure-related, socioeconomic, and institutional and policy environments, which can limit the scale of adoption of these interventions. Finally, it discusses the scale of WP improvements in rain-fed and irrigated agriculture, and qualitatively assesses their implications on future agricultural water demand. The book has seven papers, including this one.

The second paper by Amarasinghe and Sharma analyzes WP in food grains (kg/ET) in India to assess the potential scale of improvement. It uses district level data on crop yields, production, and cropped area under both rain-fed and irrigated food grain crops, along with data on crop evapotranspiration estimated using agro-meteorological data. It analyzes the role of the key determinants of overall WP of food grain crops at the regional level, such as cropping pattern, irrigation pattern, and crop consumptive use (ET), in driving WP improvements in food crops. The paper identifies three key interventions for improvement in physical productivity of water in food grain production in India, and the number of districts to which each one of them is applicable.

The third paper by Kumar, Trivedi and Singh analyzes the impact of quality and reliability of irrigation on crop WP, by comparing field level WP of major crops under well irrigation, canal irrigation and under conjunctive use of well water and canal water. This study first derives quantitative criteria for assessing the quality and reliability of irrigation water. The assessment is based on primary data on farming systems collected from farmers in two agro climatic regions of Bist Doab area in Punjab, India, which use different modes of irrigation. The paper evaluates the quality and reliability of water in canal irrigation, well irrigation and conjunctive use in quantitative terms; compares WP (both physical and economic) under different supply sources; analyzes the impact of the quality and reliability of irrigation on crop WP and cropping pattern. and identifies the factors responsible for the differential productivity.

The fourth paper by Alok Sikka presents the analysis of WP in various multiple use systems that support fisheries, tree production and dairying within the farm along with paddy, which are generally considered as a single use system. The study argues that WP assessment on the basis of the returns from crops alone and the amount of water applied and used would lead to underestimation of agricultural WP. This paper discusses the findings of research studies undertaken to assess WP in some specially designed experimental systems of multiple uses in eastern India. The various multiple water use systems include, 1) secondary reservoir cum fish pond in the tubewell command in Patna; 2) fish-trench-cum-raised bed for fish-horticulture, and rice-fish farming in seasonally waterlogged areas in Patna under the traditional rice-wheat system; 3) on–dyke horticulture and fish-prawn-poultry system, and subsurface water harvesting with fish culture in coastal Orissa; and 4) rainwater harvesting pond for fish-prawn farming with fruits and vegetables on the pond bunds in rain-fed areas of Ranchi in Jharkhand in the central plateau. This paper also discusses the impacts of introducing different production systems such as fish, prawn, horticulture and poultry in rice-wheat system on agricultural WP. Furthermore, it includes an analysis of impact of conservation technologies, viz., zero tillage-bed planting and drip irrigation on crop WP in wheat and banana, respectively.

The fifth paper by Singh and Kumar examines the factors determining water intensity of dairy farming other than climate. For this, it synthesizes empirical data available from two locations in India, viz., northern Gujarat, western Punjab, both representing semi-arid climatic conditions. But, the two regions are markedly different in terms of the nature of dairy farming. The first one is commercial dairying, which is intensive and depends heavily on irrigated fodder crops. In the second case, dairy heavily depends on by-products from crops. This paper presents the data on feed, fodder and water inputs in dairy production, expenditure on livestock keeping, milk yields, and WP in dairying for different categories of livestock. This study shows that dairy production is highly water intensive when it is commercial, and is less water intensive but efficient when it is part of mixed farming. It also shows that the nature of trade-offs involved in maximizing agricultural WP under the two situations are different. Furthermore, empirical analysis from Kerala, which is a sub-humid area, demonstrates the impact of climate change on the water intensity of dairy production. It shows that milk production is highly water-efficient in regions like Kerala, but the lack of availability of sufficient arable land becomes a constraint to intensive milk production.

The sixth paper by Kumar and van Dam discusses the various determinants for analyzing WP in Indian agriculture that are markedly different from those used in the west. It also identifies some major gaps in WP research and the key drivers of change in WP. The main arguments are 1) in developing economies like India the objective of WP research should also be to maximize net return per unit of water and aggregate returns for the farmer, rather than merely enhancing ‘crop per drop’; 2) the determinant for analyzing the impact of efficient irrigation technologies on the basin level WP and water saving should be the consumed fraction (CF) rather than evapotranspiration; 3) in closed basins, determinants for analyzing basin level WP improvement through water harvesting and conservation should be incremental economic returns and opportunity costs; 4) at the field level, the reliability of irrigation water and changing water allocation could be the key drivers of change in WP, whereas at the farm level, changes in the crop mix and farming system could be key drivers of change. In composite farming systems, measures to enhance WP should be based on farm-level analysis. At the regional level, concerns of food security, employment and markets risks can reduce the ability to significantly improve WP in agriculture.

The seventh paper by Kumar further discusses potential, prospects and constraints for improving agriculture WP in India. It first discusses the various considerations in analyzing WP in India. Some of them are: ‘scale of analyses’, i.e., field to farm to region or field to system to river basins; objective of WP assessment; food security; regional economic growth and environmental sustainability. It then discusses how integration of these considerations in analyzing WP changes the way we assess agricultural WP improvements. While new windows of opportunity for WPI are created, it also creates some new limits. For instance, taking basin as a unit for WP enhancement measures leaves us with the opportunity for improving WP using the climate advantage, as within the same basin climate often varies remarkably. It then summarizes various interventions for WP enhancement in rain-fed and irrigated agriculture, which are discussed in various papers. This is followed by a discussion of various macro-constraints in enhancing agricultural WP in rain-fed agriculture that are social, economic and financial in nature. In the case of irrigated agriculture, the constraints are physical, technological and infrastructural, institutional, market and policy related. Finally, the scale at which various WP improvement measures could be adopted in India and their potential impact on future growth in agricultural water demand is assessed.

Why is WP Improvement in Agriculture Crucial for India?

Many of India's agriculturally prosperous regions are water-scarce, where not only the natural endowment of water is poor (Amarasinghe et al. 2005), but also the demand for water in agriculture alone far exceeds the utilizable renewable water resources (Kumar et al. 2008b). The common features of these regions are excessive withdrawal of groundwater and excessive diversion of water from rivers, which cause environmental water stress. Agriculture is the major user of water in these regions, particularly for irrigated crops, with very high per capita water use in irrigation (Kumar et al. 2008c). Agriculture is in direct conflict with other sectors of water economy and environment. The scope for augmenting the utilizable water resources in these regions is extremely limited. While there are many regions in India where water resources are abundant, most of them have limited potential for increasing agricultural production due to the limitations imposed by land constraint and ecological constraints. So, improving WP in agriculture, wherever possible, holds the key to not only sustaining agriculture production and rural livelihoods, but also making more water available for other sectors including the environment.

World over, agriculture has very low water use efficiency when compared to manufacturing (Xie et al. 1993; Turner et al. 2004), and the situation is no different in India. Agriculture continues to be the largest user of diverted water in the country (Amarasinghe et al. 2008; GOI 1999). Moreover, productivity of water use in India is very low for major crops in terms of the amount of biomass produced per unit of water depleted in crop production. The reasons are many.

First: India has some of the lowest yields in cereal crops viz., wheat and rice (Amarasinghe and Sharma, Paper 2, this book). They consume large quantities of irrigation water in aggregate terms (Amarasinghe et al. 2005), compared to what is biologically possible to consume by these crops for a given variety, in the given temperature and solar radiation (Aggarwal et al. 1995). The factors responsible for this could be lack of irrigation, deficit irrigation or excessive irrigation, or lack of soil nutrient management through optimal dosage of fertilizers and micro-nutrients, poor on-farm water management or farm management. Furthermore, what is biologically possible may not be economically viable or in other words optimal. It is particularly true in areas where the soils are degraded with poor micro- and macro-nutrients, which demands application of huge quantities of nutrients to achieve the maximum yield. The latter increases the input costs, reducing the net income. Also, many crops are grown in regions where the climate is not fully favorable for realizing the good yields.

Second; irrigation water use efficiencies are poor in India (GOI 1999) due to inefficient irrigation practices or unfavorable soil conditions. Flood irrigation, level border irrigation and, to an extent furrow irrigation are generally practiced by Indian farmers for agricultural crops. The adoption of water-efficient irrigation technologies is by and large very poor to date. One example of unfavorable soil condition is the practice of growing irrigated paddy in light soils. Excessive deep percolation would require frequent watering of the crop to keep the ponding of water in the field. Another important issue is the adoption of short duration food crops, which are inherently inefficient in water use in terms of amount of grain yield per unit of water consumed (ET), but survive on rains, in vast regions of India, owing to lack of irrigation facilities.

Improving WP in agriculture can bring about many positive outcomes. While in some regions WP improvement would result in increased crop production with no increase in consumptive use of water, in some others it would result in reduced use of surface or groundwater draft. Both would protect the environment. On the other hand, there are certain regions in India where yields are very poor as the crops are purely rain-fed in spite of having a sufficient amount of unutilized water resources. Augmenting water resources and increasing irrigation in such regions can result in enhanced yield and income returns, as well as WPI. Hence, such strategies have the potential to reduce poverty in these regions.

Opportunities and Constraints for WP Improvements

As various papers included in this book show, there are several opportunities for improving the WP of crops. They include:

- providing irrigation to crops that are currently rain-fed so as to meet the full crop evapotranspirative demand for realizing the yield potential (Amarasinghe and Sharma, Paper 2, this book);
- adopting long duration food crops, which have higher water use efficiency, and replacing short duration ones, which have low efficiency, again possible through irrigation water availability (Amarasinghe and Sharma, Paper 2, this book);
- growing certain crops in regions where their yields are higher due to climatic advantages (high solar radiation and temperature for instance), better soil nutrient regimes or lower ET demand (high humidity for instance)—(Abdulleev and Molden 2004; Loomis and Connor 1996);
- improving quality and reliability of irrigation water (Kumar, Trivedi and Singh, Paper 3; Palanisami et al. 2008); the irrigation management for certain crops, which could mean controlling allocation or increasing allocation to the said crops (Kumar and van Dam, Paper 6, this book);
- adoption of high yielding varieties without increasing the crop consumptive use (Amarasinghe and Sharma, Paper 2, this book);
- provision of optimal dosage of nutrients such as artificial fertilizing; and improving farming systems with changes in crop and livestock compositions (Singh and Kumar, Paper 5; Kumar and van Dam, Paper 6, this book).

But, there are constraints to improving WP for irrigated crops induced by land availability (Amarasinghe and Sharma, Paper 2; Singh and Kumar, Paper 5, this book), food security concerning regional economic growth (Kumar and van Dam, Paper 6, this book), and existing institutional and policy frameworks. For instance, in many situations, improvement in WP in kg/ET or Rs. /ET does not guarantee better returns for the farmers due to inefficient pricing of water and electricity, and absence of well-defined property rights in water (Kumar and van Dam, Paper 6, this book; Kumar et al. 2008a). Cereals such as wheat and paddy, growing of which is important for meeting national food security needs, have much lower water use efficiency, as compared to cash crops such as cotton, castor and ground nut (Kumar and van Dam, Paper 6, this book). In case of rain-fed crops, many communities lack the knowledge and wherewithal to adopt technologies and practices to improve WP in agriculture. Finances required for investing in water harvesting systems for supplementary irrigation for rain-fed crops, and its economic viability are critical issues (Kumar, Paper 7, this book).

In a nutshell, while there seem to be great opportunities for improving WP in agriculture, to what extent this can be achieved in real practice depends on the scale at which the above said constraints operate. Also, as we have discussed earlier, to what extent the improvement in WP can be leveraged to reduce the demand for additional storage for India depends on the source of WP improvement. It is quite clear that though we can avert the need for new development of water resources for irrigation to a great extent through WP improvements, some inter-regional transfers of water saved from the committed releases in certain regions, resulting from improved WP of crops in that region, might still be required.

Institutional and Policy Measures for WP Improvements

The policy constraints concern the pricing of water used in canal irrigation and electricity used in well irrigation, whereas the institutional constraint comes from the lack of well-defined water rights for both surface water (Kumar and Singh 2001) and groundwater (Kumar 2005). Both these factors leave minimum incentives for farmers to invest in measures for improving crop WP as such measures do not lead to improved income in most situations (Zekri 2008; Kumar et al. 2008a). The electricity supplied for groundwater pumping needs to be metered and charged on a pro rata basis in regions where well irrigation is intensive. The State of Gujarat, one of the most agriculturally prosperous states in the country, has already started doing this, wherein nearly 40 % of the agricultural connections are now metered and farmers pay electricity charges on the basis of actual consumption.

The other measures that can be taken up in the short term are improving the quality of irrigation water supplies from canal systems, including provision for intermediate storage systems like the ‘diggies’ in Rajasthan (Amarasinghe et al. 2008); improving quality of power supply in agriculture in regions that have intensive groundwater irrigation, with longer duration supplies along with improved tariff structure; improving electricity infrastructure in rural areas of eastern India; provision of targeted subsidies for micro-irrigation systems in regions where their use results in major social benefits. This would help in maximizing the scale for adoption of micro-irrigation systems, and potential impacts in terms of WP improvements. On the other hand, investment in irrigation infrastructure for supplemental or full irrigation would significantly enhance crop yields in many areas and WP in some rain-fed areas. This would be a medium term measure.

Future Research

The concept of WP improvements in agriculture is relatively new. The amount of scientific assessment of WP available from research studies is heavily skewed in terms of geographical coverage, the scale of analysis, crop types, and the determinants used in assessments. These assessments mainly covered wheat, paddy and maize among food grain crops; and cotton among cash crops. Most of the assessments, which are for developed countries in the west, look at biomass output per unit of water depleted or applied and are done at the field scale looking at individual crops (Zwart and Bastiaanssen 2004; Kumar and van Dam 2008). There are quite a few unknowns in the field of WP, which can hinder making the right kind of policy decisions for managing water demand in agriculture that does not cause any undesirable consequences for the farming communities and society. We would discuss a few of them in the next.

1. The possible trade-off between improving WP of individual crops and that of the entire farm level needs to be better understood under different socioeconomic environments. For instance, while shift from irrigated paddy and wheat to water-efficient fruits and vegetables might help achieve higher crop WP, it might affect the output of milk from the farm, thereby affecting the WP of the farming system as dairying under 'mixed farming' conditions was found be highly water productive (Kumar and van Dam 2008). The unknown here is the overall value of WP in dairying under different farming conditions (Rs/m^3). Also, the risk involved in cultivation of some of the vegetables and fruits, is very high when compared to dairy farming and paddy cultivation. This is one reason why many farmers prefer to adopt the wheat-paddy system, which involves the least agronomical and market risk.

2. There is very little useful research available that can be used to estimate the WP (both physical and economic) of many perennial fruit crops. The most crucial data needed here is the amount of water consumed annually by the crop (ET) with increase in age of the plant, the change in yield over the years, and the irrigation water requirements in different years under different agro-climatic conditions. The issue of water consumption by tree crops is quite complex. While many trees consume large quantities of water, depending on the foliage, a good portion of this water comes from deep soil strata. In deep water table areas, the moisture held up in the 'vadoze zone' (hygroscopic water), which is not available for recharge or consumption by smaller plants, would provide this water. Hence, the impact of the trees on the actual water balance needs better understanding.

3. The possible trade-offs between improving agricultural WP of an individual farm and that of an entire region needs more assessment. For instance, introduction of certain cash crops might help raise the field and farm level WP, thereby benefiting the farmers who adopt it. But, extensive adoption of these crops by a large number of farmers in a region might result in increased market risk, resulting from over-production and price crash. The research question is, what should be the optimum level of adoption of such crops in different regions to save water as well as to sustain farm economy?

4. The general perception is that micro-irrigation (MI) systems help raise the WP of crops, there is sufficient analytical work now available, to show that the extent of real water saving that is possible with MI is a function of the soil, climate, geo-hydrology, and type of technology used (Kumar et al. 2008). But, unfortunately, change in applied water after adoption of the technology is often perceived as reduction in water use. When researchers proceed with their analysis of physical and economic impacts of MI systems using such assumptions, it leads to false policy prescriptions. Most of the available research on water saving and WP impacts of MI systems are based on the estimation of change in applied water. What is important is to know how the consumptive fraction (CF) changes under different climates, soils, water table conditions, and how it affects different crops.

5. WP and income improvements that are possible through the conversion of single use systems into multiple uses systems under different multiple use combinations require better understanding. This is a very crucial area for research because there appears to be several limitations to maximizing WP and income returns through the conventional route in many regions, due to physical, technological, financial and climatic constraints. For instance, in the wetlands of cold/hot and sub-humid areas, paddy is a dominant crop. It is difficult to shift from paddy to high-valued crops here. The reasons are many. Paddy is not amenable to micro-irrigation systems. Wetlands are not suitable for growing fruits and vegetables. At the same time, if the same land is also used for growing fish or shrimp, the returns could be enhanced significantly. Also, growing tree crops might enhance the returns. The biggest research challenge would be proper accounting of the water used in farms, that help assess the marginal productivity of various farming systems such as tree crops, field crops, duck-rearing and fishery.

Conclusions

With increasing water scarcities, WP enhancement in agriculture is not only relevant, but also very crucial in meeting future water demands of the agricultural and other sectors. There are several constraints in enhancing WP in agriculture. But, there are several opportunities too. However, the constraints can be reduced and the opportunities enhanced through appropriate institutional and policy interventions. WP improvement would definitely reduce the need for future investments in the new development of water resource in some regions. But, due to regional variations of water supply and use, the extent of reduction in demand for additional water for meeting future needs will not be the same as the scale of aggregate savings of water achieved by enhancing WP. However, it might result in more water being available for environmental uses or re-allocation to other sectors in some regions from what was earlier used for growing crops.

The other outcomes of WP improvement are: reduced poverty due to rise in farm income in the agriculturally backward regions; reduced environmental stresses caused by excessive pumping of groundwater or diversion of water from streams/rivers; better availability of water from basins for allocation to environmental uses or freeing up of a large amount of cultivated land under rain-fed production, resulting in increased stream flow generation from catchments. They all help meet the future water demand of different water use sectors. In fact, water productivity (WP) improvements in agriculture can be a major component in a water-sector perspective plan in India.

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Water Productivity of Food Grains in India: Exploring Potential Improvements

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Introduction

"*In broadest sense, water productivity reflects the objectives of producing more food, income, livelihoods and ecological benefits at less social and environmental cost per unit of water, where water use means per either water delivered to a use or depleted by a use. Put it simply, it means growing more food or gaining more benefits with less water.*" In: 'Water for food and Water for life' of the Comprehensive Assessment of Water Management in Agriculture (Molden and Oweis 2007).

Growing more food and gaining more benefits with less water have received significant attention recently. Many countries in the world (Seckler et al. 1998; IWMI 2001a; Rosegrant et al. 2002; de Fraiture and Wichlens 2007) and regions within countries (Amarasinghe et al. 2005, 2007a) are reaching the thresholds of physical and economic water scarcities. Physical water scarcity is primarily due to inadequate water supply for meeting increasing water demands. Economic scarcity occurs when financial costs of new water resources development projects are prohibitively high for the prevailing economy. To ensure national food security, most developing countries tend to build additional water resources either through the allocation of larger domestic funds or through borrowings from international financial institutions. One option, perhaps the most feasible one, for increasing crop production under growing water scarcity is to increase the productivity in existing uses of water. So, like the campaign for '*more crop per unit of land*' in the 1970s due to food scarcities, '*more crop or value per drop of water*' due to water scarcities is also becoming an important topic in international and national discourses.

The concept of growing more crops from every unit of land gathered momentum in the 1970s due to increasing population and shrinking per capita agricultural land availability. Food and livelihood security of an increasing population were key drivers of the 'Green Revolution' in the 1970s. A significant outcome of this campaign was a remarkable increase in crop yield or land productivity. Irrigation combined with improved seed varieties, and increased fertilizer input and farm machinery use contributed to this yield increase. However, a significant scope still exists for many countries/regions to attain higher yields. For example, India, the world's second most populous country and the largest food grain producer, still has one of the lowest land productivities. Doubling land productivity over the next five decades, although a target far below what other major crop producing countries have achieved during such a time span by now, could help India to meet most of its additional food demand. So increasing land productivity is still relevant for many countries, and regions within countries. In fact, with the decreasing size of landholding per person, improving economic productivity per unit of land should be the primary concern for India now. But, unlike five decades ago, water, a critical input for agriculture and human well-being and ecosystems, has also become a constraint in sustaining the benefits achieved so far, and expanding the irrigated areas for enhanced crop production. As a result, increasing WP is also gaining new impetus.

Increasing WP is a relatively new concept. Seckler (1996), Molden (1997) and Koppen (1999) discussed different dimensions of enhancing WP, which included *'more crop or value or job per drop of water'*. Securing more 'crop per drop' is extremely important in today's context where climate change and the energy crisis are affecting vast populations, especially the rural poor in developing nations. The initial thoughts of Seckler (1996) and Molden (1997) were vigorously pursued by various international programs led by the International Water Management Institute (IWMI)—(Rijsberman, 2003). These programs culminated in a valuable collection of studies on opportunities and potential for improving WP in different livelihood settings, agro-ecological regions, cropping patterns etc. (Kijne et al. 2003). Our attempt here is to advance the knowledge on improvements of crop water productivity at the subnational level. This is especially important for a country like India with a significant spatial variation in climate, water availability and water use, and also where most river basins are fast reaching the threshold of water resources development (Amarasinghe et al. 2005).

The focus of this study is on the assessment and potential for improvement of WP of food grain crops in India. Cereals, mainly used for food, at present, occupied 65 % of the gross cropped area in 2000 (GOI 2007) and contributes to about 65 % of total calorie supply in daily diets (Amarasinghe et al. 2007a). With changing consumption patterns, feed grains, non-grain crops and livestock production also require more land and water. Thus, future food grain requirements will have to be met with lesser amount of additional land and water, which calls for increasing land and water productivity in food grain production. In fact, if land productivity (or yield) of grains increases at a rate of 1.04 % annually, India can easily meet the projected food and feed grain requirement of about 380 million tonnes by 2050 without any addition to the consumptive water use (CWU)—(Amarasinghe et al. 2007a). In other words, such growth pattern would require no additional or perhaps less irrigation water for food production. These national level scenarios are very appealing in light of the increasing water demand in and competition from other sectors (industrial, domestic and environment) and increasing water scarcities in many productive regions. But, how can we realize such goals in vast regions with varying water and land availability and climatic conditions? We explore some directions in this paper. The study presented in this paper assesses the extent and determinants of spatial variations of WP of grains at the district level and identifies pathways of increasing WP in irrigated and rain-fed areas. Thus, the present study is a continuation of the assessment WP at the national and state level provided in Amarasinghe et al. (2007a).

Unless stated otherwise, definition of WP in this paper is *food grain production from a unit of water depleted.* Indeed, there are many definitions of WP which are based on which crop (numerator) or which drop (denominator)—(see Molden et al. 2003 for a detail discussion). Determinants of water productivity are scale-dependent, and also dependent on the objective of analysis. For crops, it relates to plant biomass per unit of transpiration, and between them there exists a linear relationship (Tanner and Sinclare 1983; Steduto and Albrizio 2005 cited in Molden and Oweis 2007). At field scale, farmers would like to know the physical production per unit of water allocated to different crops or the net return from the water delivered to the entire farm. At the level of an irrigation system, irrigation managers would be interested in knowing the value of production per unit of water delivered. Indeed, at the field or system scales, part of the water delivered is often reused within the field or system or elsewhere in the basins. Thus, for comparison between systems or between fields/farms at different locations, value of production per unit of consumptive water use (evapotranspiration) could be a better measure. The maximum of crop WP estimated in relation to evapotranspiration is close to the WP estimated in relation to transpiration under a given set of climate and soils. Thus, the difference between maximum yield and actual yield under a given agro-climatic condition shows the extent of increase in yield and WP possible through increased transpiration. For this purpose, we selected the definitions of WP of food-grains as the ratio of production and the crop consumptive use.

There are mainly two potential ways of increasing WP of food grains in India. First, is by increasing food grain yield with little or no additional CWU. There are a large number of low productivity areas having high potential for increasing crop yields by combining better water management, including improving reliability of irrigation deliveries in irrigated areas or providing a little supplementary irrigation in rain-fed areas, and agronomic practices and technology inputs. Second, is by reducing the amount of water depleted in irrigation with only little or no negative impacts on the yield. Water thus saved can be used for expanding the cultivated area and increase crop production or for beneficial uses in other sectors (Kumar and van Dam 2008). These are essentially areas receiving intensive irrigation and high dosage of crop inputs such as fertilizers and pesticides, and recording high crop yields, but with high incidence of overirrigation resulting in non-beneficial evaporation.

We have focused on potential contribution of higher crop yield and lower CWU in increasing the WP in different districts in India. It first identifies low productivity but high potential zones where a provision of supplemental irrigation could boost both the yield and WP significantly. It also identifies high productivity zones where there is a great possibility of water saving per unit of land, with little or no loss of production, or expanding production frontiers with no extra provision of irrigation water. In the next section, we discuss the methodology for achieving this and the data used for the study. In section three, we explore pathways of increasing WP and crop outputs. We conclude the paper with a discussion on policy implications.

Methodology and Data

Assessment and identifying determinants for improvement in WP of food grains is the main focus of this paper. Food grains consist of rice (milled equivalent), wheat, maize, other coarse cereals (sorghum, pearl millet, maize, ragi, barley and small millets) and pulses (gram, tur and other pulses)—(GOI 2007). Total food grain production per unit of CWU (kg/m^3) defines

WP in this paper. The CWU in irrigated areas is potential evapotranspiration (ETa)[1] during crop growth periods of different seasons and is given by

$$CWU_{ij}^{IR} = Area_{ij}^{IR} \text{ X} \left(\sum_{k\varepsilon \text{ growth periods}} Kc_{jk} \text{ X} \left(\sum_{l\varepsilon \text{ months}} Et_{ikl}^{p} \right) \right)$$

for the jth crop in the ith season. Where Kc's are the crop coefficients that vary over four growth periods and Et^Ps are monthly reference evapotranspiration. ETa essentially is the aggregate of effective rainfall (ERF) and the net irrigation requirement (NET).

CWU in rain-fed areas is only the effective rainfall during the season, and is estimated as

$$CWU_{ij}^{RF} = Area_{ij}^{RF} \text{ X} \sum_{k\varepsilon \text{ growth periods}} \min \left(Kc_{ik} \sum_{l\varepsilon \text{ months}} Et_{jkl}^{p}, \sum_{l\varepsilon \text{ months}} ERF_{jkl} \right)$$

where ERF_{jkl} is the effective rainfall of ith month in the kth growth period. The total annual CUW of a district is estimated as

$$CWU = \sum_{i\varepsilon \text{ seasons}} \sum_{l\varepsilon \text{ crops}} \left(CWU_{ij}^{IR} + CWU_{ij}^{RF} \right)$$

And the total WP is estimated by

$$WP = \frac{\sum_{j\varepsilon \text{ crops}} average\ yield_{j} \text{ X} \left(Area_{i}^{IR} + Area_{j}^{RF} \right)}{CWU}$$

where food grains consist of rice, wheat, maize, other coarse cereals and pulses (see Amarasinghe et al. 2005, 2007a for more details).

First, this study maps and gives a brief account of spatial variation in WP across states and districts in India (Figure 1).

Here we estimate the total WP across states and districts and assess the determinants of spatial variation. We use a multiple regression to assess implications of access to irrigation and other input use on spatial WP variation. We use total CWU as a proxy for availability of water supply for crop production, and percentage of groundwater irrigated area as a proxy for reliability of irrigation. In general, groundwater, with its easier control in operations, is more reliable than canal irrigation. However in some cases, pumping water in groundwater irrigation can be as unreliable as canal irrigation supplies because of the former dependency on an unreliable electricity supply for such pumping.

Second, it assesses pathways of increasing WP at the district level and their potential for irrigated and rain-fed land areas. This potential varies in different CWU regions (A, B and C in Figure 2). With increasing CWU, both maximum yield and WP increases in CWU region A, yield increases but WP decreases in region B and both yield and WP decreases in region C.

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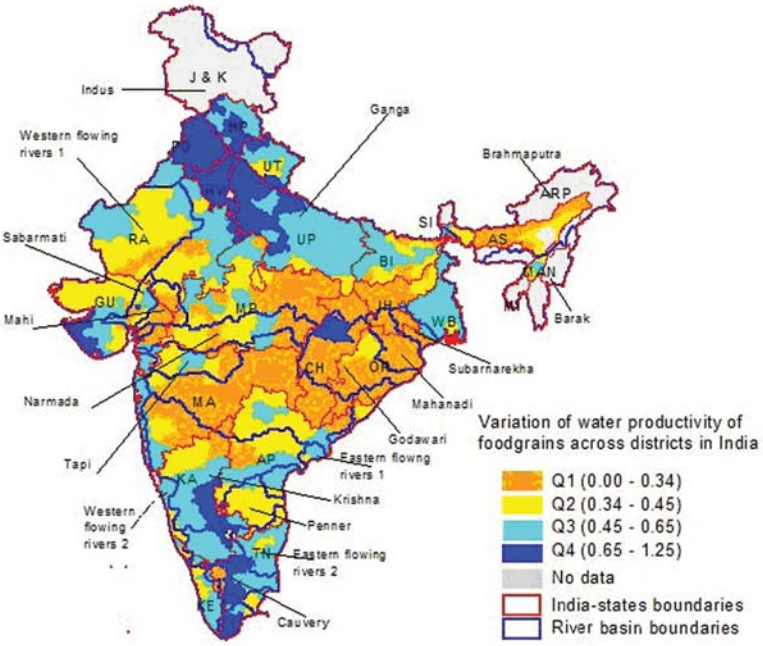
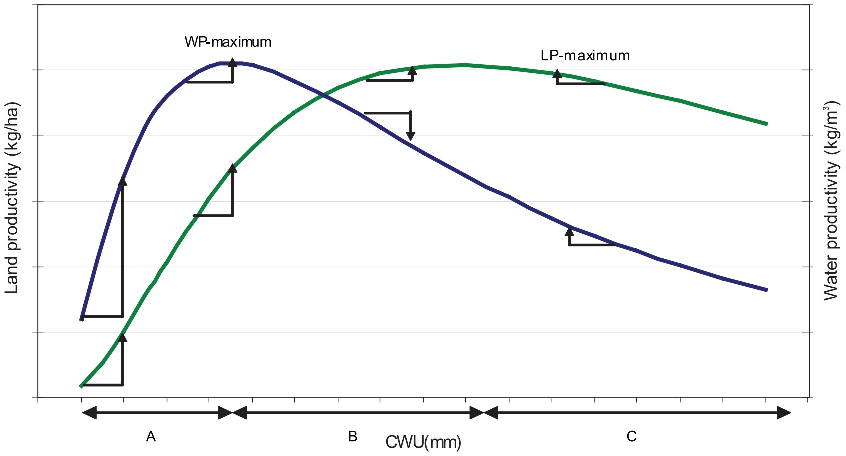
[1] In some areas, the actual evapotranspiration could be less due to deficit irrigation or nonoptimal field conditions.

Figure 1. State and river basin boundaries in India with variation in water productivity of food grains across districts.



Source: Based on authors' estimates

Figure 2. Pathways of increasing WP.



We hypothesize that a significant potential exists for increasing WP and production through:

- Bridging the gap between the actual and the maximum land productivity (yield). This can be done at any level of CWU in regions A, B and C in Figure 2, where a significant gap exists between actual and maximum yield. Maximum yield is the one that is attained under the current level of water and other agronomic and technological inputs.
- Providing additional irrigation to increase CWU in region A (Figure 2). These are mainly rain-fed areas, and a small increase in CWU can generate a large increase in land and water productivity and production. A comparable increase in CWU in region B would result in smaller growth in yield and hence production. However, additional CWU would decrease WP in region B. These areas need diversification of crop production or agriculture patterns to increase the economic value of water productivity.
- Practicing deficit irrigation for not meeting the full water requirement in irrigated areas. This potential exists in CWU region C (Figure 2). Reducing CWU in this region would, in fact, increase land and water productivity and, hence production. Many a time, these are the irrigated areas with large irrigation application and poor water management. Thus, deficit consumptive water use with proper water management can have large benefits in terms of irrigation demand and food production.

To explore these opportunities at the district level, we estimate the relationships between yield and CWU and WP and CWU. First, we estimate the maximum land and water productivity, which are attained at different levels of CWU. For this, we use two to three of the largest yield values at different CWU regimes (0-50 mm, 50-100 mm, 100-150 mm, etc.,) and estimate the maximum yield function. Next, we assess the potential for yield or WP improvements through additional, supplementary and deficit irrigation.

Data for the study consists of district level land use and crop production for 2000 (averages of 1999-2001). Three-year averages smoothen the deviations due to high short-term temporal climatic variations. For the analysis at district level, we look at the extent of irrigated and rain-fed areas of different crops, and the combined total production. These were collected from the Government of India and other sources (FAI 2003a-d; GOI 2002, 2007). Climate data (monthly potential evapotranspiration and rainfall) for the study was available from Climate and Water Atlas (IWMI 2001b). We consider 403 districts in 20 major states namely, Punjab, Haryana, Uttar Pradesh (UP), Himachal Pradesh (HP), Uttarankhand, Jammu and Kashmir (in the north); Bihar, West Bengal (WB), Assam, Jharkhand (in the north-east), Orissa and Andhra Pradesh (AP) —(in the east), Tamil Nadu (TN), Kerala, Karnataka (in the south), Maharashtra and Gujarat (in the west), Rajasthan (in the north-west)and Madhya Pradesh (MP) and Chattisgarh (in central India). These districts contribute to about 99 % of the consumptive water use and 98 % of the production of food-grains in India (Amarasinghe et al. 2008b).

Water Productivity of Food Grains – Present Status

At present, WP of food grains in India is significantly lower when compared to other major food-grain producing countries in the world (Molden et al. 1998; Rosegrant et al. 2002; Cai and Rosegrant 2003). In 2000, WP of food-grains in India was only 0.48 kg/m^3 of CWU. This was primarily due to low growth in yields. India's food grain yield was 1.7 tonnes/ha in 2000, which has increased only by1.0 tonnes/ha during 1960-2000 (FAO 2005). Meanwhile, China with a similar level of yield in 1960 (0.9 tonnes/ha) has increased to about 4.0 tonnes/ha by 2000. The USA made vast strides by increasing food grain yield from 2.5 tonnes/ha in 1960 to 5.8 tons/ha over the same period. Also, India produces less grain in spite of having a large cropped area (205 million tonnes in 124 million ha), while China and USA have much larger production (using less water) from a significantly smaller crop area. Indeed, India has significant scope for raising the levels of WP by increasing its crop yield alone. Better water management can create additional increase in WP in many regions.

Variations of Water Productivity among States

WP varies from 1.01 kg/m^3 in Punjab (the highest) to 0.21 kg/m^3 in Orissa (the lowest) among states (Table 1).

These differences are mainly due to varying cropping and land-use patterns, yield levels and CWU. Among the large variations, we observe: Punjab, Haryana and Uttar Pradesh (UP) in the Indo-Gangetic basin (IGB) are having the highest water productivities. These states, with rice-wheat dominated cropping pattern, share 26 % of the total CWU in India, but contributing to 40 % of the total food grain production. Importantly, they contribute to 70 % of wheat and 26 % of rice production in India. A major part of the area under food grain in these states is irrigated. It is 67, 85 and 97 % in Uttar Pradesh, Haryana and Punjab, respectively, and contributing to 48, 72 and 75 % of the CWU.

Low share of irrigation to total CWU in Uttar Pradesh means that effective rainfall contributes to a significant part of CWU. In fact, substantial variation in WP too exists within Uttar Pradesh. For example, water productivity in 53 districts in Uttar Pradesh varies between 0.40 to 1.02 kg/m^3. Western region with 20 districts has 34 % of the grain area, contributing to 40 % of the total food grain production. Average WP in the western region is 0.75 kg/m^3. Eastern and Bundelkhand regions encompassing 23 districts have 48 % of the area under food grains, contributing to 42 % of the total food grain production. Average water productivity in these two regions is only 0.54 kg/m^3. A key difference between the western and eastern and Bundelkhand region is in the irrigated area, where 82 % of the area is irrigated in western region against 54 % in the eastern and Buldelkhand region.

- Bihar, also in the IGB, with 82 % of the area under wheat and rice, however, has lower WP and share 6.2 % of CWU and 5.9 % of the food-grain production in India. Irrigation contributes to 60 % of the area and 33 % of the CWU in Bihar. Although a major part of the grain area is irrigated, effective rainfall meets much of the CWU in Bihar at present. Irrigated areas contribute to 65 % of total CWU in Bihar, but irrigation contributes to only 51 % of CWU in irrigated areas.

- Andhra Pradesh, Tamil Nadu, West Bengal and Kerala with rice-dominated cropping patterns (more than 80 % of grain area) have slightly higher WP. These states share 19 % each of total CWU and total grain production of India. While irrigation contributes to major part of CWU in Andhra Pradesh and Tamil Nadu (47 % and 58 %), it contributes to only 15 % and 26 % of the CWU in West Bengal and Kerala.

Table 1. Water productivity of grains across states of India.

ID	State[1]	Area (Million ha), production (Million mt), CWU (km^3), NET and WP (kg/m^3) of grains																
		Total							Irrigation							Rain-fed		
		CWU	NET	Area	Production	Yield	CWU	WP	CWU - % of total CWU	NET - % of irri-CWU	Area % of total area	Production % of total	Yield	CWU	WP	Yield	CWU	WP
		km^3	km^3	M ha	M Mt	tonne/ha	mm	kg/m^3	%	%	%	%	tonne/ha	mm	kg/m^3	tonne/ha	mm	kg/m^3
	India	424	154	123	205.4	1.66	344	0.48	56	65	43	68	2.59	446	0.58	0.95	265	0.36
1	Uttar Pradesh	71.4	34.4	20.3	43.4	2.13	351	0.61	73	66	68	83	2.61	377	0.69	1.13	296	0.38
2	Maharashtra	36.1	6.1	13.3	11.3	0.85	272	0.31	26	66	15	22	1.25	461	0.27	0.78	238	0.33
3	Andhra Pradesh	33.5	15.8	7.3	14.3	1.96	460	0.43	77	61	56	82	2.86	628	0.45	0.81	243	0.33
4	Madhya Pradesh	31.3	14.3	11.2	11.1	0.99	278	0.36	51	90	34	48	1.39	417	0.33	0.78	207	0.38
5	West Bengal	29.5	4.5	6.6	15.2	2.31	447	0.52	44	35	42	50	2.73	461	0.59	2.00	436	0.46
6	Orissa	28.4	2.1	6.5	6.1	0.93	434	0.21	36	21	29	49	1.53	535	0.29	0.68	392	0.17
7	Bihar	26.3	8.7	7.1	12.1	1.71	373	0.46	64	52	60	72	2.06	400	0.51	1.19	332	0.36
8	Rajasthan	25.7	13.4	11.7	11.7	1.00	220	0.46	57	92	29	61	2.12	435	0.49	0.55	134	0.41
9	Punjab	25.4	18.9	6.3	25.5	4.07	404	1.01	99	76	97	99	4.14	411	1.01	1.79	184	0.97
10	Karnataka	20.3	5.7	7.5	9.9	1.32	272	0.49	42	66	23	44	2.51	495	0.51	0.96	204	0.47
11	Chattisgarh	18.3	2.2	5.1	4.8	0.94	362	0.26	30	40	21	32	1.42	513	0.28	0.81	322	0.25
12	Tamil Nadu	16.4	9.5	3.5	8.7	2.47	463	0.53	85	68	60	83	3.38	650	0.52	1.09	178	0.61
13	Haryana	15.6	11.2	4.3	13.4	3.13	363	0.86	92	78	85	95	3.51	395	0.89	0.98	185	0.53
14	Assam	13.9	0.1	2.8	4.1	1.45	492	0.29	8	7	8	13	2.51	522	0.48	1.36	489	0.28
15	Gujarat	10.6	4.4	3.8	4.2	1.11	280	0.40	55	76	29	47	1.81	533	0.34	0.83	178	0.47
16	Jharkhand	7.7	0.3	1.9	2.0	1.08	409	0.26	8	41	8	12	1.66	442	0.38	1.03	406	0.25
17	Uttaranchal	3.0	0.7	1.0	1.7	1.75	298	0.59	53	43	38	57	2.59	408	0.63	1.22	229	0.53
18	Jammu &Kashmir	2.4	1.0	0.9	1.2	1.38	271	0.51	63	64	37	40	1.48	455	0.33	1.32	161	0.82
19	Himachal Pradesh	2.0	0.2	0.8	1.5	1.78	245	0.73	27	34	19	21	2.03	353	0.58	1.73	220	0.79
20	Kerala	1.7	0.4	0.4	0.8	2.17	470	0.46	65	41	57	64	2.45	538	0.45	1.82	381	0.48
21	Others[2]	5.3	0.4	1.3	2.2	1.68	404	0.42	34	7	31	45	2.43	443	0.55	1.35	386	0.35

Source: Authors' estimates

Notes: 1- states are ordered in descending order of total CWU

2- Others include Nagaland, Maipur, Megalaya, Mizoram, Sikki, Tripura, Arunchal Pradesh and union territories (Andaman and Diu, Dadra and Nagar Haveli, Delhi, Goa, Lakshdweep, Pondicherry)

- Orissa, Chattisgarh and Jharkhand, in eastern India, have the lowest water productivities, and share 12.8 % of the total CWU, contributing to only 6.3 % of the food grain production. These are major rain-fed states where rice dominates the cropping patterns. In Orissa and Chattisgarh, 26 and 21 % of the area under food grains are irrigated, but irrigation contributes to only 8 and 12 % the CWU, respectively. The share of irrigated area (8%) and contribution from irrigation to CWU (3%) are even smaller in Jharkhand.

- Maharashtra, Madhya Pradesh, Karnataka and Gujarat with a mixture of cropping patterns (more than 50 % of the area under maize, other coarse cereals and pulses) have lower water productivity. They share 27 % of CWU and contribute to 21 % of food grain production in India. Irrigation in Maharashtra and Karnataka covers only 15 and 23 % of area, respectively, contributing to 17 and 28 % of CWU. However, irrigation in Madhya Pradesh and Gujarat covers 29 % of the area under food grains, contributing to 52 and 41 % of the CWU.

Extent of irrigation and cropping patterns partly explain the variation in water productivity among the states. Presence or absence of irrigation (irrigated and rain-fed areas) mainly explains the variation in total water productivity.[2] Additionally, the land use and cropping patterns of food grains significantly influence water productivity differences between states.

In 2000, irrigation covered 43 % of the area under food grains, but contributed only to 68 % of the total production. While many opportunities still exist in improving WP in irrigated and rain-fed conditions with the existing level of water use or with proper cropping patterns, shifting production frontiers of rain-fed food grain crops through new irrigation could also boost WP significantly. These regions require not only better water management but also better non-water input application. Depending on CWU and actual irrigation at present, improvements in WP with better water management require various interventions-—from full irrigation to small supplemental irrigation, no additional irrigation to deficit irrigation. We discuss these in detail in the next section by assessing functional relationships of yield versus CWU at the district level. Before that we present the spatial variations of WP across the districts in India.

Variations in Water Productivity among Districts

District-wise water productivity values vary between 0.11 kg/m^3 to 1.25 kg/m^3 (Figure 1, Annex Table 1). WP in the first to fourth quartiles (Q1-Q4) vary from 0.11- 0.34, 0.34-0.45, 0.45- 0.60 and 0.60-1.25 kg/m^3). Districts in the fourth quartile of water productivities account only 22 % of the total area under food grains and 22 % of total CWU, but contribute to 38% of total food grain production of all districts in this study (Figure 3). Irrigation provides water supply to 72 % of the total area under food grains in this group, and contributes 81 % of total CWU and

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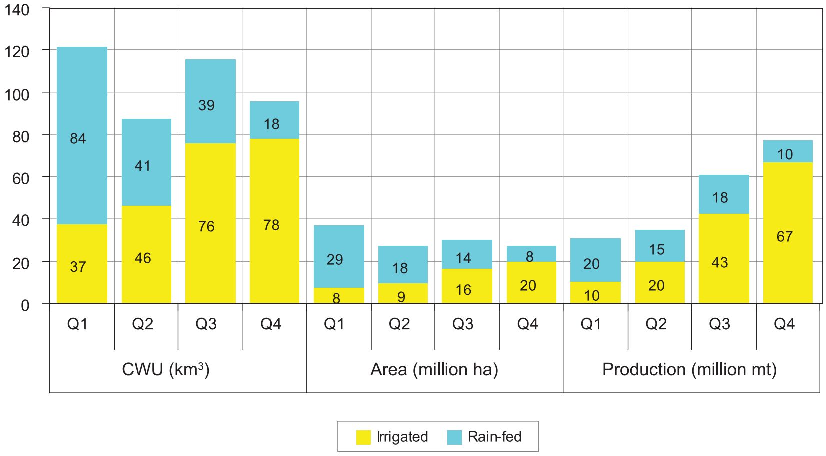
[2] WP = 0.021 + 0.59 IWP + 0.37 RWP + 0.11 PCGRIRAR-0.09 PCRIAR, Adjusted R^2= 97%
(.029) (0.06) (0.05) (0.05) (0.02)

Values within parentheses are standard errors of estimates. TWP, IWP and RWP are total, irrigated and rain-fed water productivity, PCGRIRAR is irrigated grain area as a % of total grain area and PCRIAR is percentage of area under rice.

Figure 3. CWU, area and production of food grains.



Source: Authors' estimates

87 % of total food grain production. In irrigated areas, net evapotranspiration (NET) accounts for 72 % of CWU.

On the other hand, districts in the first quartile of water productivities account 30 % of total area under food grains and 29 % of total CWU, but they contribute to only 15 % of total crop production. Effective rainfall, the main source of water supply in this group, accounts 83 % of the total CWU.

These observations show irrigation is a major contributor to higher yields and hence to the production in these districts, and they in turn contributed to higher water productivity. Further analyses (Table 2)[3] show that in districts with a substantial irrigated grain area (i.e., districts with percentage of irrigated grain area more than 25 %):

1) Relative increase in WP is significantly higher when actual yield is much lower than the maximum yield. Every 1 % increase in yield increases WP by 0.65 % (first regression in Table 1). Large potential of increasing WP exist in areas where both yield and CWU are significantly low or in areas where CWU is high but yield is significantly lower than the maximum. There are many districts with significantly high CWU, but with a significant gap between maximum and the actual yield. It is in these areas that there exists a high potential for reducing the yield gap and increasing WP with better water and input management. Part of the reasons for a low yield gap in areas with high CWU could be agro-climatic factors. In these areas, only a proportionate increase in CWU can increase the yield and WP (Molden and Oweis 2007).

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[3] Note: First regression in Table 2 assess the extent that variation of yield explains the variation of WP. The last two regressions asses the contribution of differences of CWU (mm), fertilizer application per gross cropped are, and groundwater irrigated area as a percent of gross irrigated area explain the variation of yield and WP. To some extent, fertilizer application/ha show the extent of application of non-water inputs. Ground irrigated area could be considered to indicate the reliability of irrigation water supply.

Table 2. Regressions of yield and WP of food grains.

Explanatory variable	Coefficients (standard errors) of explanatory variables (n = 255)		
	Ln (WP)	Yield	WP
Ln (Yield) (tonne/ha)	0.66 (0.027) *	-	-
Constant	-5.59 (0.19) *	356.0 (196.0) *	0.60 (0.1) *
Total CWU (mm)	-	1.5 (0.5) *	-0.0009 (0.0001) *
Fertilizer application/gross cropped area (kg/ga)	-	8.1 (0.6) *	0.002 (0.0001) *
Groundwater irrigated area - % of gross irrigated area	-	3.6 (1.1) *	0.0008 (0.0001) *
Adjusted R^2	59%	51%	41%

Note: *- Statistically significant at 0.001% level

2) Average yield increases, but WP decreases with increasing CWU. This indicates that at present, the rate of increase in average yield is lower than the rate of increase of CWU with an increase in irrigation inputs.

3) Higher fertilizer inputs are significantly associated with higher yields and WP. Groundwater irrigation contributes significantly to increasing yield and also WP. This perhaps indicates that, in spite of a negative relationship between WP and increasing CWU, reliable irrigation deliveries, in this case through groundwater, can have a significant positive effect in increasing both WP and yield.

Molden et al. (2003) suggest improvements of non-water inputs with better water management could be an effective strategy for increasing yield and WP in many regions. The above regression results also show that better management of irrigation and non-water inputs can substantially increase food grain yield and WP. In fact, we observe that significant variations exist in yield and WP at different levels of irrigated grain area (i.e., 0-10 %, 10-20 %, 20-30 %, 30-40 % etc., of the total area), where coefficients of variation (CV=standard deviation/average) of yield and WP vary from 20 to 51 and 23 to 50 %, respectively, and decreases with increasing irrigated area. The smallest CV of yield is in districts where the percentage of the irrigated area is between 70 to 80 %, while the largest CV of yield is in districts where the percentage of the irrigated area is between 20 to 30 %. This shows that there still is great scope for increasing the yield and hence WP at any given level of the irrigation patterns. However, opportunities for increasing yield through better management of water and non-water inputs are higher in districts with high CWU.

Additional irrigation could be a major boost for increasing yield in many districts with low CWU or low irrigated area. In fact, recent research (Sharma et al. 2006) indicates that providing a small supplemental irrigation of about 100 mm during critical water stress periods of crop growth can significantly increase crop yields in major rain-fed districts of India. Sharma et al. (2006) and

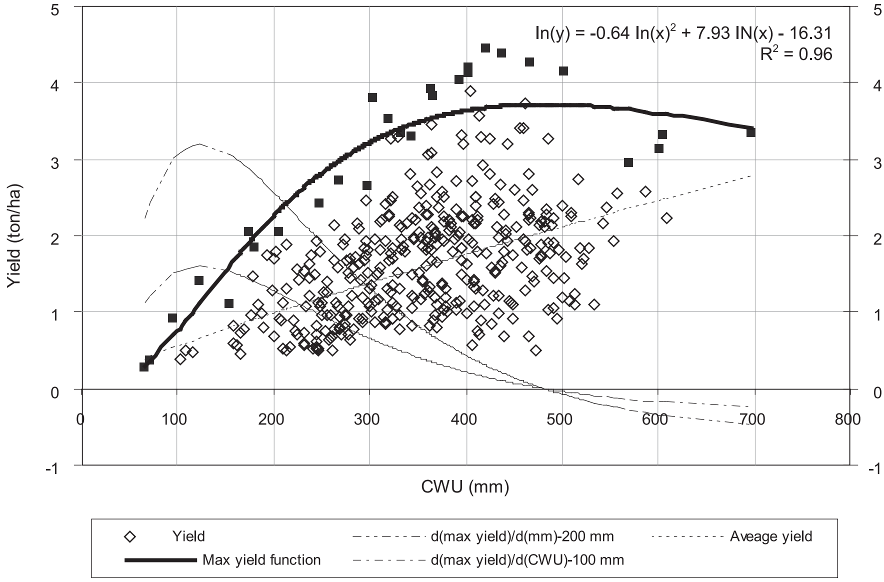
Wani et al. (2003) show that rainwater can be managed through in situ harvesting to provide supplemental irrigation to increase yields in rain-fed cropping systems. Significant scope also exists for increasing the yield and WP in many districts with moderate to high irrigation inputs. All these offer opportunities for increasing the numerator, i.e., production in WP estimation.

Is there scope for increasing WP by changing the denominator, i.e., the consumptive water use? In fact, many canal irrigation systems in water-scarce north-western parts of India are good examples where this is already happening (Malhotra 1982; Perry and Narayanamurthy 1998; Sakthivadivel et al. 1999). Due to water scarcity water delivery in these systems uses the *warabandi*[4] principle. The farmers practice deficit irrigation in a larger area at the expense of meeting full requirement of a smaller area with a view to maximizing returns to a unit of water delivered and consumed. Deficit irrigation could be a good strategy for increasing WP where water is scarce but land is not (Molden et al. 2003; Kumar and van Dam 2008). And as shown by Oweis and Hachum (2003), such practices can result in significant increase in crop output too. We explore these in the next section.

Some Pathways of Improving WP in India

Figure 4 shows that several strategies exist for increasing WP in Indian districts. X-axis in Figure 4 represents consumptive water use (mm), while Y-axis represents food grain yield (1,000 kg//ha) and growth in yield (in 1,000 kg) per every additional unit of CWU. Average

Figure 4. Relationships of yield and consumptive water use (CWU) of food grains.



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[4] Warabandi, where‘wara’ means turn, and ‘bandi’ means fixed, is a rotational system of irrigation delivery with turns are fixed according to a predetermined schedule specifying the day, time and duration of supply (Malhotra 1982). Warabandi promotes equity of water distribution in a larger area than adequate water supply to a small area.

yield function takes Cob-Douglas form (ln(yield) = 2.48-.18 ln(CWU), R^2= 0.29). We use 2-3 highest values of yield in each category of CWU (0-50, 50-100, 100-150, 150-200, etc.,) for estimating the maximum yield function. Figure 4 also depicts two marginal yield curves (d [max yield]/d [CWU]) for increase in CWU of 100 and 200 mm.

Figure 4 also shows that all three hypotheses that we mentioned earlier exist in food grain production in Indian districts:

1) A significant gap exists between maximum[5] and actual yields in many districts, with the magnitude of the gap increasing with increasing CWU;

2) A significant marginal gain in maximum yield can be achieved with additional CWU in low to moderate CWU districts. These are mainly the districts with large rain-fed areas; and

3) Little or no gain in maximum yield can be achieved by increasing CWU in moderate to high CWU districts.

So, WP of districts can be increased by:

- increasing the numerator (or yield)
- by reducing the gap between actual and maximum yield with or without increasing the CWU in districts with moderate CWU, and
- by increasing CWU in low CWU regions

Decreasing the denominator (or CWU) without losing any yield or overall production benefits to a unit of water consumed at all in mainly irrigated districts with high CWU.

Diversifying agriculture to high-value crops or livestock in rain-fed or irrigated regions with moderate to high CWU, where further increase in yields of food grains is not possible by increasing CWU.

Reducing Yield Gap

With large gaps between actual and maximum yield, first strategy in improving WP should be increasing yield without additional CWU, and hence without additional irrigation. To better understand the dynamics of WP variations, we divided the district into two groups. First group has districts with an irrigated grain area of less than 25 % of the total area under food grains, where rain-fed food grain production dominates. There are 158 districts in this group and the total CWU in rain-fed area is 79 % of the total CWU (see Annex Table 1). The other group has an irrigated grain area of more than 25 % of the total grain area. There are 251 districts in this group and the total CWU of irrigated area is 72 % of the total CWU, and more than half of CWU in the irrigated area is from irrigation water supplies.

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[5] The maximum yield attained at present could however, vary from one agro-climatic zone to other. So, the gap between the actual yield and the maximum attained at present as indicated in Figure 3 for some districts could be slightly lower.

There are 32 districts (25 from the first group, 7 from the second group) with yield gaps more than 75 % of maximum yield ,162 (86 and 76 from the two groups) districts with yield gaps between 50 % to 75 % of maximum yield, 151 (31 and 120 from the two groups) districts with yield gaps between 25 %-50 % of maximum yield and 58 districts has yield gaps less than 25 % of maximum yield (10 and 48 from the two groups)—(see maps on the left in Figures 4 and 5 for the locations). Maps on the right in Figures 5 and 6 show the absolute gap between actual and maximum yield.

Figure 5. Yield gap in food grains in districts with irrigated area under food grains less than 25% of the total area.

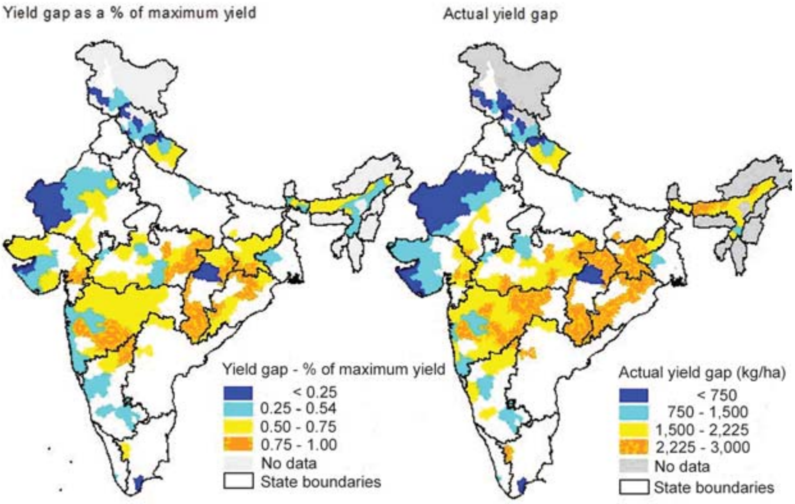
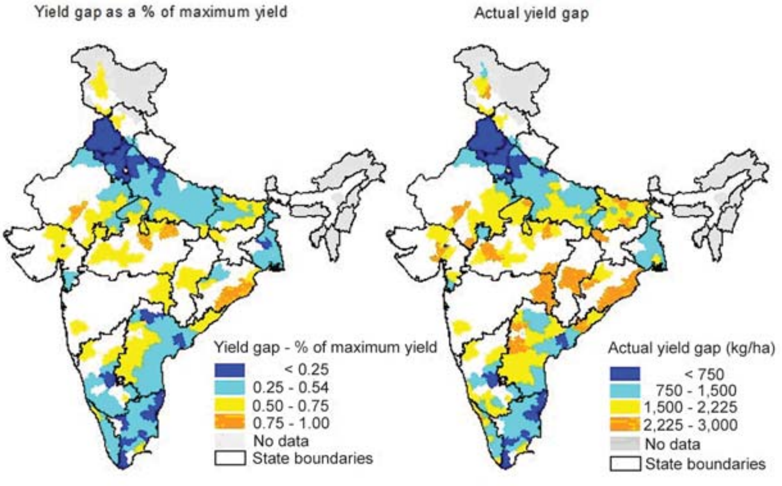


Figure 6. Yield gap of food grains in districts with irrigated area under food grains more than 25% of the total area.

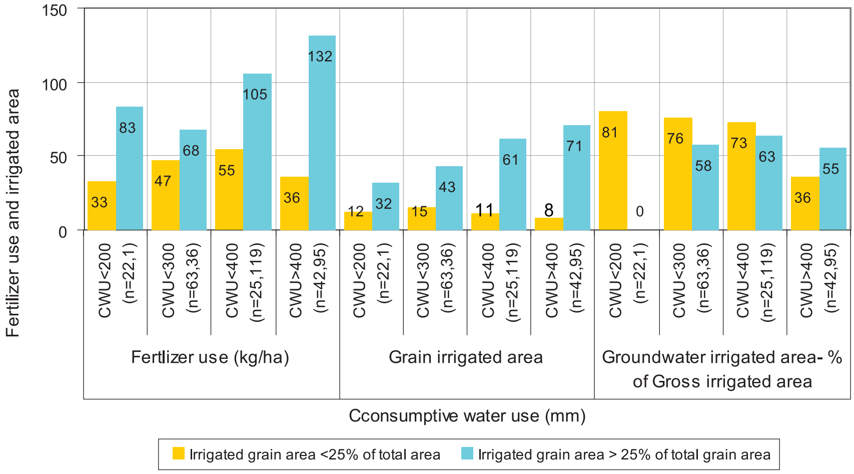


If the gap between actual and maximum grain yield of each district can be reduced by 25 %, total production could be increased from 203 to 252 million tonnes. If increase in yield is possible without increasing CWU, WP would increase from 0.48 to 0.60 kg/m^3. A reduction in yield gap by 50, 75 and 100 % without increasing CWU could increase production to 300, 349 and 397 million tonnes, respectively, and WP to 0.72, 0.83 and 0.97 kg/m^3, respectively. The latter requires only little over 1% yield increase annually, and the resultant total production is adequate for meeting the grain demand in 2050 (Amarasinghe et al. 2007a).

Indeed, reducing the yield gap without increasing consumptive water use or simply without additional irrigation offer significant opportunities for increasing production and WP. This shall be possible through better adoption of improved/ hybrid varieties in both rain-fed and irrigated areas, better targeting of nutrient requirements/deficiencies, timely completion of farming operations, control of plant diseases and pests and a better synchronization between crop water requirements and irrigation supplies in irrigated areas.

Many districts with a large proportion of the area under irrigated grain production (irrigated area under food grains >25 % total grain area) have yield gaps exceeding 25 % of maximum yield (Figure 6). The actual yield gap in most of these districts is more than the average yield at present (1,660 kg/ha), and majority of the CWU in irrigated areas of these districts are from irrigation water supply. These districts have high potential for reducing the yield gap without increasing CWU, through better in situ management of rains, and irrigation water management. We also observe that districts with a large irrigated area under food grains with large CWU have relatively high level of fertilizer use (Figure 7, see Annex Table 1). Thus better management of non-water inputs with existing irrigation supply could reduce most of the gap in the yield in these districts. This group, with 261 districts (Figure 6), contributes 53 % of total area under food grains, 80 % of total irrigated grain production, and share 79 % of total CWU through irrigation. Reducing the yield gap by 25, 50, 75 and 100 % in these districts could increase production by 17, 34, 51 and 68 %, respectively, from the level of production in 2000.

Figure 7. Fertilizer use at different levels of CWU.



Source: Authors' estimates

Note: Figures within parenthesis in the X-axis are numbers of districts with irrigated area <25% and >25%, respectively

The districts which are mainly rain-fed, i.e., districts with less than 25 % of its food grain area under irrigation, also have large yield gaps. The CWU of 55 % of these districts is less than 300 mm, and fertilizer application in those is very low compared to irrigated grain area. The quantity and reliability of the water supply, especially from rainfall are the biggest constraints for increasing input application and hence yield in this group. If yield is to increase in these districts, they require additional irrigation combined with better management of non-water inputs. This is the focus of in the next section.

Providing Additional Irrigation

Second strategy for improving WP is providing additional irrigation. The districts with low CWU have the highest potential for increasing yield by increasing CWU (Figure 4). Marginal yield curves (d [max yield]/d [CWU]) show that increasing CWU could significantly increase the maximum yield in many districts with low CWU. With 100 mm of additional CWU, the maximum yield can be doubled in districts with less than 150 mm of CWU (see d (yield)/d (CWU)-100 mm curve). With 200 mm of additional CWU, the yield can be doubled in districts with less than 225 mm of CWU. Many of these districts can increase the yield by providing small to moderate irrigation or by increasing the amounts of effective rainfall through in-situ conservation and storage.

However, growth in the food grain yield with supplemental irrigation decreases in districts with high CWU. Both scenarios of supplemental irrigation (100 or 200 mm), marginal growth in yield decreases and become negative after 475 mm of CWU (Figure 4). This is also due to the fact that most food grain crops grown under rain-fed conditions (sorghum, pearl millet, local maize and small millets) have very low values of harvest index with only a fraction of biomass converted into grain yields. If increasing yield is the sole objective then providing additional irrigation (with existing crops and their varieties) would only benefit districts with CWU of less than 475 mm.

However, growth in WP becomes negative in many districts with CWU being well below 475 mm (Figure 8). Figure 8 depicts district level variation in WP with respect to CWU. Marginal WP curves (d[max WP]/d[CWU]) show that additional irrigation can more than double maximum WP in districts with only low CWU (below 150 mm). The WP growth becomes negative with additional irrigation after 225 mm of CWU. For assessing the potential benefits with additional irrigation, we consider three subgroups of districts: subgroup 1 with a total CWU of below 225 mm, subgroup 2 with total CWU of between 225 and 475 mm and subgroup 3 with a total CWU of above 475 mm.

Subgroup 1: There are 39 districts in this category (first group of map A and B in Figure 9).[6] And 38 of them belong to districts with an irrigated area of food grains below 25 % of the area under food grains. These districts share 12 % of the total area under food grains but contribute to only 4 % of the food grain production at present. More than 80 % of the area in these districts is rain-fed. In fact, the CWU of rain-fed areas (map E, Figure 8) contributes the most

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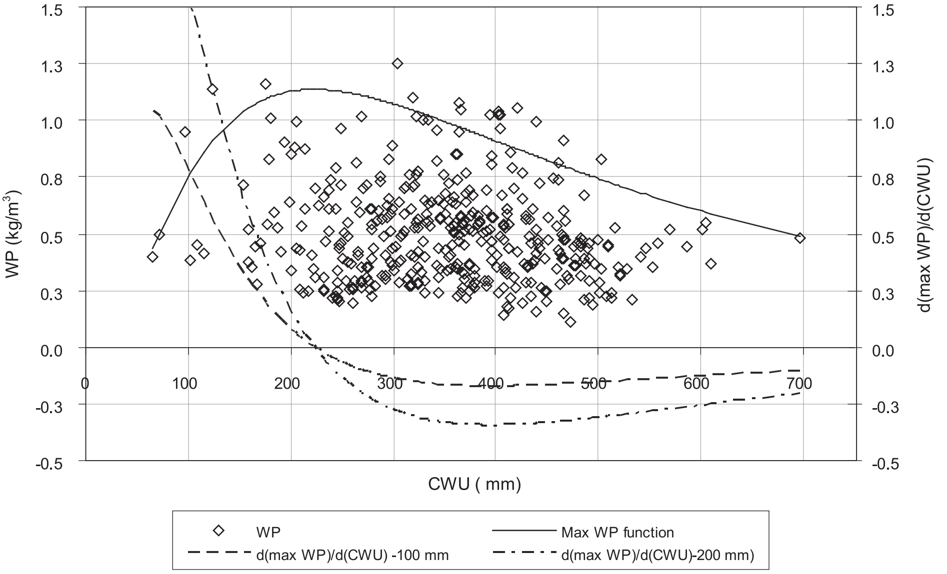
[6] Figure 8 shows two sets of maps indicating the variation of CWU in districts with irrigated area under food grains less and more than 25% of total area, respectively. Maps A and B show the variation of average CWU in the two groups. Maps C and D show the variation of CWU of irrigated areas, and maps E and F show the variation of CWU in rain-fed areas.

Figure 8. Relationships in water productivity (WP) and consumptive water use (CWU) of food grains.



Source: Based on authors' estimates

to the average CWU of these districts. With the present level of yield and WP frontiers, additional irrigation in rain-fed areas could increase both the maximum yield and WP in these districts. To illustrate the benefits of additional irrigation on production and WP gains, we use a marginal increase in maximum yield with respect to small increases in CWU. We estimate that with 100 mm (or 200 mm) of additional CWU, these 39 districts can increase their total food grain production and WP by 83 % (or 167 %), and 15 % (or 22 %), respectively.

In fact, average grain yield of many districts in subgroup 1 are significantly lower than the maximum yield at any given level of CWU. Sharma et al. (2006) found that water stress in critical periods of crop growth is a key determinant of low yields in these rain-fed areas. So, with proper application of a small quantity of supplemental irrigation in water stress periods by itself could reduce the yield gap, and additional irrigation with better application of non-water inputs could push up the average yield in parallel to the increasing path of maximum yield. Thus, cumulative benefit of additional irrigation in these districts could be much higher than what is illustrated above.

Subgroup 2: There are 316 districts in this category (second and third groups of map A and B). At present, they contribute to 79 % of total area under food grains and 84 % of total production. Figure 9 and Figure 8 show that increasing CWU would increase the yield but decrease WP in districts with a CWU total of between 225 mm and 475 mm. For example, with 100 mm of additional irrigation, this group as a whole can increase the total food grain production along the path of maximum yield only by 11 %, reducing WP by 10 %.

However, this does not mean that increasing CWU would decrease WP in all areas of these districts. Rain-fed area under food grains of subgroup 2, which is 57 % of the total rain-fed area under food grains, can further be divided into smaller classes. This consists of 57 % of the total rain-fed area under food grains.

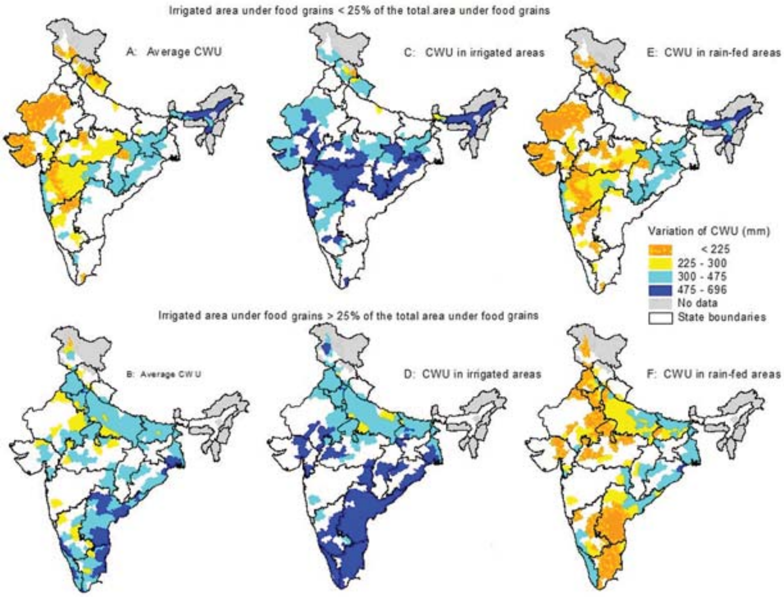
- 119 districts in subgroup 2 have rain-fed areas under food grains with CWU (=effective rainfall) below 225 mm (map F in Figure 9). As in subgroup 1, supplemental irrigation in the rain-fed areas of these districts can also significantly increase both food grain yield and WP.

- Also, rain-fed areas under food grains of 110 districts have a CWU of between 225 and 300 mm (map F in Figure 9). These areas can also increase food grain yield with supplemental irrigation. But the extent of increase in WP depends on the gap between actual and the maximum yield.

So essentially, rain-fed areas under food grains of 268 districts (39 in subgroup 1, and 229 in subgroup 2) can increase yield, WP or both by increasing CWU through supplemental irrigation, provided that non-water inputs are closely integrated with additional irrigation applications.

Irrigation covers 46 % of the total area under food grains of districts in group 2. Among them, irrigated area under food grains of 15 districts has a CWU below 300 mm (map D in Figure 9). These districts can also significantly benefit from a small supplemental irrigation combined with better non-water input management. Among the remaining districts in group 2, irrigated area has rather a high total of CWU, and irrigation contributes to more than half of the total of CWU (CWU above 300 mm in map D in Figure 8). Increasing CWU through additional irrigation would not contribute much to increase yield or WP. However, unreliable irrigation water supply, combined with inadequate or improper application of other inputs, is the key factor responsible for substantial yield gaps. Therefore, better management of existing water and non-water inputs can still increase production and WP in irrigated areas of all these districts.

Figure 9. Spatial distribution of CWU in irrigated and rain-fed food grains areas across districts.



Source: Based on authors' estimates

Subgroup 3: This consists of districts with a total CWU of above 475 mm. Increasing CWU above 475 would have negative incremental benefits on both yield and WP. There are 48 districts in this group and they account for 14 and 15 % of total area under food grains and production (CWU above 475 mm in map A and B). Some of the districts in this group are major rain-fed areas with a high percentage of rice cultivation. They can improve both land water productivity by adopting hybrid rice with higher yield, or increase value of water productivity with integrated farming systems with crop-aquaculture. In irrigated areas, WP can be increased by reducing the CWU through deficit irrigation. We will discuss the implication of CWU reduction through deficit irrigation next.

Reducing CWU through Deficit Irrigation

Third strategy for increasing WP is to decrease consumptive water use through deficit irrigation. Main objective of deficit irrigation is to increase the water use efficiency by eliminating non-beneficial evaporation or non-recoverable deep percolation that do not contribute to transpiration and hence have little impact on crop yields. The resulting yield reduction may be small in comparison to benefits gained through diverting the saved water to irrigate other crops for which water would be insufficient under traditional irrigation practices (Kirda and Kanber 1999). In irrigated areas with more than 475 mm of CWU, this strategy could increase both yield and WP. In regions with a CWU of between 225 and 475 mm, it can only increase WP. However, even with some loss of yield this strategy can save water and then use that saved water for increasing crop production or in another productive use. To illustrate the positive impacts on crop production, we develop a few scenarios of reducing CWU and the resulting water savings and production increases (Table 3).

The data shows two deficit CWU scenarios of 25 and 50 mm (column 1, Table3) in districts with more than 25, 50 and 75 % irrigated area under food grains (column 2). In each category, we consider only districts with less than 10 % and 5 % and no yield reduction due to deficit CWU (column 3). Columns 4-7 show the total area under food grains, CWU in the irrigated area, NET part of the irrigated CWU and total food grain production, respectively. Columns 8 and 9 show the saved CWU as a percentage of NET in the irrigated area under food grains, and the net gain in production if the saved water is again used for additional grain production.

About 251 districts (Figure 10) with more than 25 % of irrigated food grain area will have 10 % less food grain yield with 25 mm of deficit CWU (column 3, Table 2).

This group of districts account for 63 % of the total food grain area in the country, contributing to 79 % of the total food grain production. Deficit CWU of 25 mm on existing irrigated area can save 14 % of the NET requirement. If all that saved NET are again used for expanding food grain production, it can contribute to 8 % additional production. Deficit CWU of 50 mm can save 27 % of NET and can increase 17 % of production.

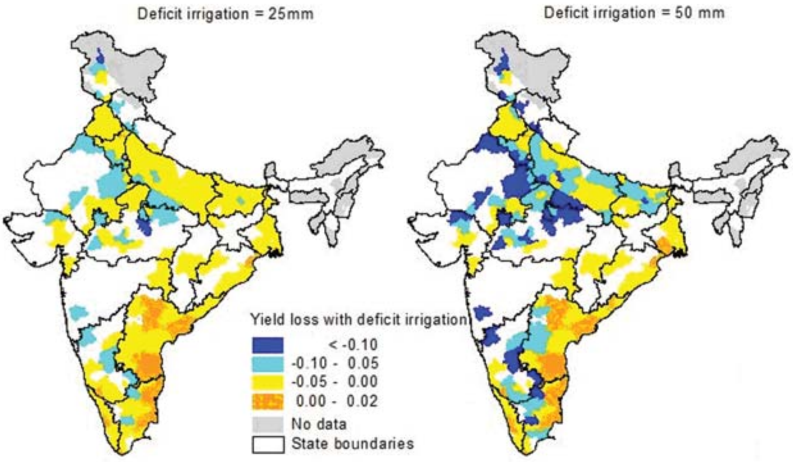
Reduction in CWU can increase grain production in all districts having a significant irrigated area (Table 2). However, such strategy can help the most in increasing production in districts that are poorly-endowed in water, but not of land. Almost all districts with 25 mm deficit CWU would, in fact, gain in yield or have yield loss less than 5 % (Figure 9). Number of districts with yield loss greater than 10 % would increase from 5 % with a 25 mm deficit of CWU to 43 % with a 50 mm of deficit CWU. Good strategy here is to increase deficit CWU to the extent that gains in benefits, whether in crop production or through other uses of the saved water are greater than value of the production loss due to yield decrease. The above example illustrates that many

Table 3. CWU saved and net gain in food grain production through deficit irrigation.

Deficit in CWU	Irrigated food grain area -% of total	Yield loss -% of max yield	Number of districts	Grain area	Irrigated CWU	NET	Grain production	Saved CWU-% of NET	Net gain in food grain production - % of total
(mm)	%	%	#	Million Ha	Km^3	Km^3	Million Mt	%	%
25	>25	<10	251	77	211	136	161	14	8
		<5	213	64	191	119	142	14	8
		<0	26	8	33	19	18	10	9
	>50	<10	165	50	166	110	123	11	7
		<5	153	46	158	103	117	11	7
		<0	25	7	33	19	18	9	8
	>75	<10	78	24	90	61	70	10	6
		<5	77	23	89	60	69	10	6
		<0	13	2	11	7	6	7	7
50	>25	<10	213	64	191	119	142	27	17
		<5	144	45	148	87	104	26	18
		<0	26	8	33	19	18	20	18
	>50	<10	153	46	158	103	117	22	15
		<5	110	34	127	79	89	22	16
		<0	25	7	33	19	18	19	17
	>75	<10	77	23	89	60	69	19	14
		<5	59	18	72	48	54	19	14
		<0	13	2	11	7	6	14	15

districts with substantial irrigated area can gain in food grain production by practicing 25 mm deficit irrigation. However, the main question here, as raised by Kumar and van Dam (2008), is whether there is adequate land for using the saved water for additional crop production. Most of the districts which can benefit from deficit irrigation lie in Indus, Ganga, Mahanadi, Godavari, Krishna and Cauvery basins (Figure 10). It is well-known that parts of north-west in the Indus and Ganga basin, practice deficit irrigation in canal command areas. Rice-wheat is the dominant cropping pattern in these basins. Among the other four basins, Krishna and Cauvery are water- stressed basins. Even with some loss of crop production, the Krishna and Cauvery basins can gain the most through the deficit irrigation concept. However, to what extent the existing cropping pattern allow deficit irrigation in these districts is another question. Rice dominates the irrigation cropping patterns in these basins, and they often use substantially more water in excess of Eta— the crop water requirement. However, studies show that different irrigation techniques such as wet and dry irrigation (Sakthivadivel et al. 2001), system of rice Intensification can increase both yield and water use efficiency in irrigated rice, which results in increased production and WP. Where and to what extent these techniques can be adopted and their benefits on major rice irrigated areas need further assessment.

Figure 10. Yield loss with different deficit irrigation strategies.



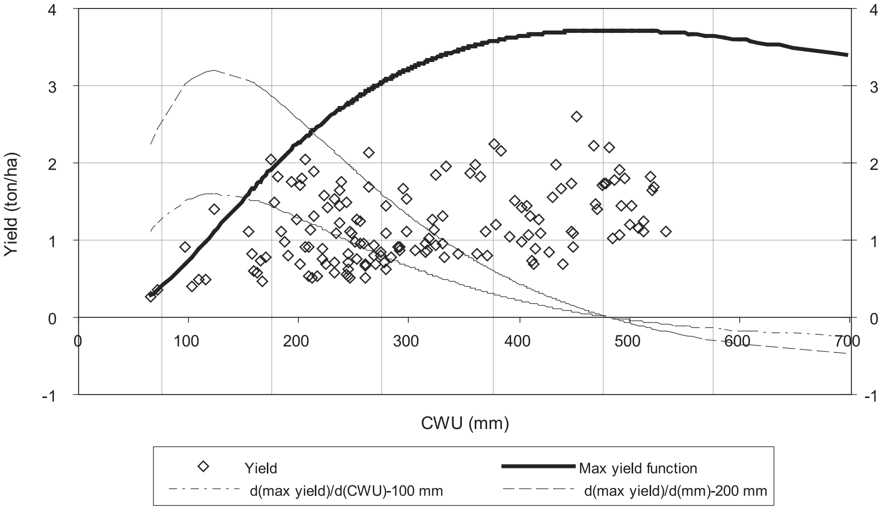
Source: Based on authors' estimates

Increasing Water Productivity in Rain-fed Districts

Figure 11 shows the variation of grain yield in the 155 districts with mainly rain-fed agriculture, i.e., districts with less than 25 % of the total cropped area under irrigation. These districts have two-thirds of the total food grain area of India, contributing to only one-third of the food grain production. About 14 % of districts in this category have extreme dry conditions with a CWU of below 200 mm, and another 58 % of districts have moderate to low dry conditions (where CWU is between 200 and 400 mm). The cropping pattern explains a major part of low WP in this group. Due to low rainfall, less water-intensive crops such as coarse cereals and pulses dominate the grain cropping patterns in these districts. More than 70 % of the area under food grains consists of coarse cereals and pulses. Average yields of these crops (0.87 tonnes/ha of coarse cereals, and 0.55 tonnes/ha of pulses) compared with rice, wheat and maize (1.97, 2.82, and 1.82 tonnes/ha respectively) are very low. As discussed previously, a small supplemental irrigation could significantly increase existing grain yields and WP in many districts, particularly in those with CWU below 225 mm.

About a quarter of the districts in this category also have CWU between 400 and 535 mm, with rice as the major food grain crop. Effective rainfall contributes to almost all the total CWU of these districts. Although total rainfall is adequate for rice cultivation in these districts, rice yields are very low due to many factors including a mismatch between crop water demands and rain water availability periods. Such conditions discourage the farmers from making investments in farm inputs. As such, these districts have one of the lowest fertilizer application in India (36 kg of NPK /ha), which is only one-fourth of the fertilizer application in all other districts with similar CWU (135 kg of NPK/ha). Thus, an unreliable water supply from rainfall alone seemed to be a major impediment for proper input application and low rice yield in these districts. As availability of water is not a significant constraint, small supplemental irrigation during periods of input application and in critical periods of water stress could increase the yield in these districts. Another option is to change cropping patterns to best utilize the

Figure 11. Yield versus CWU of districts with grain irrigated area less than 25 % of total.



Source: Based on authors' estimates

water supply from rainfall. The demand for feed crops such as maize and vegetable oils are increasing rapidly and substantial part of this demand is projected to be imported from other countries (Amarasinghe et al. 2007b). Thus, changing cropping patterns from low-yielding rice to high-yielding maize or oil crops, especially in the rabi season could generate significant benefits for these regions. In fact, soil moisture through rainfall could be more than adequate for raising productive maize or oil crops in these regions.

Discussion and Conclusion

Our assessment using district-level data show that significant potential exists for increasing WP of food grains with substantial increase in production. Almost all districts can employ different types of water management interventions that can contribute to increasing water productivity and production, thus ensuring food and livelihood security and employment generation. These interventions vary from small to moderate supplemental irrigation to deficit irrigation. Small to moderate supplementary irrigation inputs can increase yield, WP or both in areas where CWU is below 300 mm. In fact, CWU (or the effective rainfall) of rain-fed areas in 158 districts falls below the threshold of 225 mm (districts indicated by 'A' in columns 19 and 21 in Annex Table 1). Irrigated areas of 15 districts and rain-fed areas of 110 more districts have CWU between 225 to 300 mm (districts indicated by 'B' in columns 18 and 20). The data of 1995/96 shows that India has more than 111 million agricultural landholdings covering 141 million ha of net sown area (GOI 2007). Of this, about 66 % of landholdings and 74 % cropped area are either partly irrigated or completely rain-fed. In this category, 28 % of the landholdings consist of 67 % of semi-medium (2-4 ha) to medium (4- 10 ha) and large (>10 ha) holding sizes. A significant part of this area is covered by food grain crops. These are the areas that can benefit through small to moderate supplemental irrigation and can have a significant impact on WP as well as on crop production. Increased production contributes to food and livelihood security of farmers of these areas.

What are the options for improving crop water productivity in marginal (<1ha) to small (1-2 ha) holdings in partially irrigated to rain-fed lands? Nearly 72 % of India's marginal and small landholdings are in partially irrigated or rain-fed land category, but they only have 33 % of the cropped area. Although it was not analyzed in this paper, the cost of providing supplemental irrigation to marginal and small landholdings could be higher than the benefits through production increase in food grains. As argued by Kumar and Dam (2008), it is in these holdings where the objective should be increasing value of agricultural productivity but not increasing water productivity of crops, and importantly that of low-value food grain crops. These areas could benefit with crop diversification to high-value crops or livestock production with additional supplemental irrigation.

Supplemental irrigation increases crop yield but decreases WP when CWU is between 300 and 475 mm. The CWU in irrigated areas of 219 districts and in rain-fed areas of 227 districts falls in to this category (districts indicated by 'C' in columns 19 and 21 of Annex Table 1). If availability of water is not a constraint, these areas can benefit from a small supplemental irrigation. If water availability is a constraining factor, increasing productivity of land should be the major focus. In fact, we observed that there is a substantial difference between the actual and maximum yield in these districts. Most of the variation in food grain yield is explained by variation in water and non-water inputs. Better water management improves non-water input application, which leads to higher productivity and production.

In irrigated areas, this means providing a reliable irrigation supply. One way of achieving this is through introducing intermediate water storage structures as in the Indira Gandhi Nehar Project in Rajasthan (IGNP)—(Amarasinghe et al. 2008). The intermediate water storage structures, called '*diggies*', in the IGNP store the water delivered from the watercourses to farms. Next it pumps water out of the *diggi* and distributes it to the field through field channels or sprinklers. It helps to supply irrigation when crop requires it the most. Thus, *diggies* simply improve the reliability of water application to crops, and hence improves application of non-water inputs too. Most importantly, *diggies* help introduce micro-irrigation in the canal command areas. All these interventions contribute to higher yield, production and WP. However, *diggies* are shown to be cost-effective for landholdings above 4 ha. Thus, *diggies* can directly help medium to large fully irrigated landholdings. In India, 8 % of the irrigated landholdings are in this category, and they account for 24 % of the irrigated land. Does this mean that small to semi-medium landholdings cannot benefit from intermediate water storage structures? Perhaps not! But it requires new types of institutions of water users. Like water user associations (WUAs) at the level of watercourses, small number of small landholdings ranging from 4 to 6 can form user groups, which share a common *diggi*. Such user group can reduce the cost of construction of *diggies* and improve performance of irrigation deliveries to farms. Understanding of the institutional mechanisms that requires for successful implementation of such water user groups is beyond the scope of this paper. However, a good lesson for a similar intervention can be seen in the areas under 'system tanks' in Tamil Nadu. Benefits from such interventions can be further enhanced by exploring the possibility of integrating aquaculture into the *diggies*/ system tanks/ intermediate storage structures.

Rain-fed areas with moderate CWU, i.e., between 300 and 475 mm, require different strategies for reducing the yield gap. One option for improving water productivity in these areas is to promote agricultural diversification to high-value crops and livestock. This should be done in areas where soil moisture is adequate for raising high-value non-grain crops or fodder that is required for livestock. This is mainly in areas in the upper end of CWU region, i.e., those close to 475 mm. In other areas, increasing water productivity may not be the proper goal. These areas, as in low CWU rain-fed zones, could greatly benefit from some small supplemental irrigation in critical water-stressed periods. Although this does not result in increases in WP, the benefits from production increase may outweigh the cost of supplemental irrigation. To know to what extent the benefits outweigh the cost requires further research.

Irrigated areas with high CWU can benefit by reducing CWU. This increases both yield and WP. The water saved from deficit irrigation can again be used to increase crop production, if land is not a limiting factor. If the latter is true, the water saved can be used for productive purposes in other sectors. In India, 48 districts which account for 13 % of the total irrigated food grain area have CWU more than 475 mm (districts indicated by ‘D’ in columns 19 in Annex Table 1). The data presently available with us, however, do not show, whether all this area belongs to semi-medium to large landholdings.

Reducing crop consumptive use in irrigated areas, where CWU is below 475 mm, can also increase grain water productivity. Although the crop yield will marginally decrease in this case, water saved through reduction of CWU can again be used for expanding the cropped area. This can be practiced in places where increase in production through area expansion offsets the loss of production due to yield loss. Our results show irrigated areas in many districts with CWU below 475 mm can increase grain production (we have indicated only the districts with CWU in irrigated area above 425 mm, and they are denoted by ‘CD’ in column 19 of Annex Table 1). Once again, to what extent this actually can be done depends on the size of the landholding.

Finally, we focused our attention on rain-fed areas with large CWU (districts indicated by ‘E’ in column 20 of Annex Table 1). At present, paddy crop dominates cropping patterns of these areas and have a very low yield. This may be mainly due to cultivation of low- yielding local varieties and a mismatch between crop water demands and periods of rain water availability. Efforts should be made on both these fronts. Alternatively, these areas should diversify their cropping patterns. One option is to diversify to feed grains such as maize or non-grain crops such as oil crops. Both require less CWU than rice and also could be more productive than rice crop. With increasing demand for feed grains and vegetable oils, this could be a good option for these rain-fed regions.

In this paper, we have only discussed the potential for increasing WP and production through water management practices. We assumed that better water management would lead to better non-water input application and, which in turn will increase the crop yield and WP. However, many other factors affect the mode of water management or crop or agricultural diversification in different regions. They include reliability of power supply, availability of roads, access to markets, extension services etc. To know how these would influence the success in implementing different water management interventions require more data and research. Moreover, advances in biotechnology could help develop seed varieties that withstand droughts and conditions of water-stress or increases the yield frontiers with the existing levels of water consumption by the crop. All these would increase WP and crop production.

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Annex Table 1. Water productivity variations across districts in India.

ID	Districts[1]	State	Total and Irrigated area (Million ha), production (Million mt), CWU (km^3), NET and WP (kg/m^3) of grains															
			Total					Irrigation				Other data						
			Area	Production	Yield	CWU	WP	CWU - % of total CWU	NET - % of irri CWU	Area - % of total	Production - % of total	Grian area - % of GCA	Grian irri. area - % of GIA	NIA - % of NSA	GIA - % of GCA	GWIRA - % of GIA	CWU in irrigated grain area	CWU in rain-fed grain area
			M ha	M Mt	tonne/ha	mm	kg/m^3	%	%	%	%	%	%	%	%	%	mm	mm
1	The Dangs	GU	0.05	0.05	1.0	250	0.4	0	33	0.0	0.0	82	2	1	1	100	329 C	250 B
2	Darjiling	WB	0.07	0.12	1.8	364	0.5	1	93	1.2	1.6	37	7	23	7	45	238 B	366 C
3	Puruliya	WB	0.32	0.63	2.0	434	0.5	1	71	1.6	2.2	81	12	32	10	16	376 C	435 C
4	Dhanbad	JH	0.09	0.10	1.1	419	0.3	1	88	1.6	2.6	98	30	5	5	66	336 C	421 C
5	Bidar	KA	0.39	0.21	0.5	245	0.2	4	89	1.7	4.2	84	15	13	9	100	554 D	240 B
6	Thane	MA	0.18	0.34	1.9	356	0.5	3	37	2.0	3.3	71	28	6	5	100	555 D	352 C
7	Mandla	MP	0.35	0.21	0.6	245	0.3	4	80	2.1	3.6	71	48	4	3	18	467 CD	241 B
8	Ratnagiri	MA	0.11	0.22	2.0	361	0.5	4	30	2.4	3.8	45	25	1	4	28	526 D	357 C
9	Amravati	MA	0.36	0.34	0.9	292	0.3	5	98	2.4	3.8	36	12	8	7	100	546 D	285 B
10	Jalpaiguri	WB	0.29	0.45	1.5	431	0.4	2	95	2.8	3.8	59	21	31	8	94	254 B	436 C
11	Gumla	JH	0.22	0.18	0.8	427	0.2	3	31	3.0	4.7	92	34	4	8	32	473 CD	425 C
12	Barmer	RA	1.11	0.29	0.3	66	0.4	21	94	3.0	10.6	66	20	6	10	99	465 CD	53 A
13	Sindhudurg	MA	0.09	0.19	2.2	384	0.6	4	29	3.0	4.8	57	15	24	12	1	525 D	380 C
14	Bastar (Jagdalpur)	CH	0.75	0.61	0.8	362	0.2	5	34	3.2	5.4	89	90	3	3	13	511 D	357 C
15	Churu	RA	0.70	0.35	0.5	109	0.5	12	91	3.2	11.4	62	25	12	8	63	399 C	99 A
16	Akola	MA	0.54	0.50	0.9	290	0.3	7	100	3.5	5.4	49	30	3	6	59	560 D	280 B
17	Bharuch	GU	0.32	0.18	0.6	232	0.2	8	75	3.5	7.3	75	14	22	19	83	517 D	222 A
18	Buldana	MA	0.47	0.46	1.0	255	0.4	8	100	3.7	5.8	57	36	5	6	96	562 D	244 B
19	Ranchi	JH	0.22	0.28	1.3	418	0.3	4	39	3.9	6.1	93	47	8	8	85	424 C	418 C
20	Dhule	MA	0.51	0.45	0.9	221	0.4	10	97	3.9	6.1	64	24	12	11	100	559 D	207 A
21	Dumka (Santal Pargana)	JH	0.18	0.26	1.4	408	0.4	4	56	4.1	6.4	98	60	6	7	57	375 C	409 C
22	Jhabua	MP	0.17	0.11	0.7	200	0.3	9	75	4.2	7.2	49	28	6	8	64	438 CD	190 A
23	Kolhapur	MA	0.20	0.40	2.0	333	0.6	7	91	4.3	6.8	28	6	26	21	34	554 D	323 C
24	Pashchimi Singhbhum (Ch.)	JH	0.22	0.15	0.7	439	0.2	5	18	4.4	6.9	99	84	4	5	2	523 D	435 C
25	Jamnagar	GU	0.06	0.05	0.9	97	0.9	22	98	4.4	9.0	8	2	14	16	98	494 D	78 A
26	Hamirpur	HP	0.07	0.12	1.7	200	0.9	9	52	4.4	5.1	96	88	5	5	3	433 CD	190 A
27	Purbi Singhbhum	JH	0.17	0.16	0.9	449	0.2	5	16	4.4	6.9	100	99	2	4	3	520 D	446 C

(Continued)

Annex Table 1. Water productivity variations across districts in India (*Continued*).

ID	Districts[1]	State	Total and Irrigated area (Million ha), production (Million mt), CWU (km^3), NET and WP (kg/m^3) of grains															
			Total					Irrigation				Other data						
			Area	Production	Yield	CWU	WP	CWU - % of total CWU	NET - % of irri CWU	Area - % of total	Production - % of total	Grian area - % of GCA	Grian irri. area - % of GIA	NIA - % of NSA	GIA - % of GCA	GWIRA - % of GIA	CWU in irrigated grain area	CWU in rain-fed grain area
			M ha	M Mt	tonne/ha	mm	kg/m^3	%	%	%	%	%	%	%	%	%	mm	mm
28	Yavatmal	MA	0.41	0.39	0.9	314	0.3	8	99	4.6	7.2	43	24	6	8	66	564 D	302 C
29	Gulbarga	KA	1.70	0.91	0.5	217	0.2	9	62	4.7	11.4	90	45	13	9	24	429 CD	207 A
30	Sahibganj	JH	0.11	0.16	1.5	396	0.4	4	61	4.9	7.7	96	51	7	9	9	347 C	398 C
31	Raigarh (Alibag)	MA	0.15	0.35	2.2	377	0.6	7	32	5.3	8.2	73	68	6	6	38	528 D	368 C
32	Udhampur	JK	0.11	0.16	1.4	227	0.6	9	49	5.5	6.1	98	105	8	5	0	390 C	217 A
33	Kullu	HP	0.05	0.10	2.0	175	1.2	10	42	5.7	6.7	80	88	7	5	0	298 B	168 A
34	Lohardaga	JH	0.05	0.05	1.0	402	0.2	6	55	6.1	9.4	88	54	9	10	44	378 C	403 C
35	Surguja (Ambikapur)	CH	0.57	0.49	0.9	315	0.3	9	37	6.1	10.1	88	93	6	6	18	479 D	305 C
36	Marigaon	AS	0.13	0.22	1.7	476	0.4	7	7	6.4	11.1	83	97	6	5	0	515 D	473 C
37	Koch Bihar	WB	0.32	0.53	1.7	437	0.4	6	40	6.4	8.6	63	83	7	5	100	376 C	442 C
38	Nanded	MA	0.46	0.40	0.9	292	0.3	11	81	6.5	10.0	57	29	8	13	100	512 D	277 B
39	Karimganj	AS	0.08	0.14	1.8	487	0.4	7	5	6.5	11.4	81	97	6	5	0	491 D	487 E
40	Cachar	AS	0.11	0.25	2.2	482	0.5	7	5	6.8	11.8	78	97	6	5	0	491 D	482 E
41	Giridih	JH	0.07	0.09	1.3	410	0.3	6	78	6.8	10.6	85	35	10	17	72	341 C	415 C
42	Nagaon	AS	0.27	0.48	1.7	477	0.4	7	10	6.8	11.9	78	97	6	5	0	516 D	475 C
43	Raigarh	CH	0.57	0.47	0.8	344	0.2	10	35	6.9	11.4	94	90	8	7	30	490 D	334 C
44	Nalbari	AS	0.16	0.18	1.1	512	0.2	7	8	6.9	12.0	77	97	6	5	0	534 D	511 E
45	Hajlakandi	AS	0.05	0.08	1.7	478	0.4	7	6	6.9	12.0	77	97	6	5	0	487 D	478 E
46	Kamrup	AS	0.20	0.29	1.4	492	0.3	7	6	6.9	12.0	77	97	6	5	0	514 D	490 E
47	Goalpara	AS	0.08	0.12	1.4	470	0.3	8	6	7.0	12.1	76	97	6	5	0	512 D	467 C
48	Bongaigaon	AS	0.11	0.12	1.1	491	0.2	7	7	7.0	12.1	76	97	6	5	0	525 D	488 E
49	Kokrajhar	AS	0.11	0.12	1.2	508	0.2	7	7	7.0	12.2	76	97	6	5	0	521 D	507 E
50	Deoghar	JH	0.07	0.10	1.4	402	0.4	6	74	7.1	11.0	83	60	8	10	34	344 C	406 C
51	Barpeta	AS	0.23	0.23	1.0	485	0.2	8	7	7.3	12.6	72	96	6	5	0	527 D	482 E
52	Shahdol	MP	0.45	0.35	0.8	283	0.3	10	93	7.3	12.2	86	93	7	7	36	476 D	274 B
53	Hazaribag	JH	0.17	0.20	1.2	379	0.3	6	78	7.3	11.3	88	42	15	15	66	328 C	384 C
54	Jodhpur	RA	0.89	0.42	0.5	115	0.4	30	95	7.3	23.1	70	32	11	16	92	479 D	86 A

(Continued)

Annex Table 1. Water productivity variations across districts in India (*Continued*).

ID	Districts[1]	State	Total and Irrigated area (Million ha), production (Million mt), CWU (km^3), NET and WP (kg/m^3) of grains															
			Total					Irrigation				Other data						
			Area	Production	Yield	CWU	WP	CWU - % of total CWU	NET - % of irri CWU	Area - % of total	Production - % of total	Grian area - % of GCA	Grian irri. area - % of GIA	NIA - % of NSA	GIA - % of GCA	GWIRA - % of GIA	CWU in irrigated grain area	CWU in rain-fed grain area
			M ha	M Mt	tonne/ha	mm	kg/m^3	%	%	%	%	%	%	%	%	%	mm	mm
55	Karbi Anglong	AS	0.13	0.20	1.5	469	0.3	8	5	7.4	12.8	72	97	6	5	0	488 D	468 C
56	Dhubri	AS	0.17	0.19	1.1	450	0.2	9	8	7.5	13.0	71	97	6	5	0	514 D	444 C
57	Lakhimpur	AS	0.11	0.12	1.1	533	0.2	8	5	7.8	13.4	68	97	6	5	0	545 D	532 E
58	Bilaspur	HP	0.06	0.11	1.9	214	0.9	16	48	7.9	9.2	97	88	11	9	3	434 CD	195 A
59	Nashik	MA	0.64	0.48	0.8	222	0.3	17	84	7.9	12.1	68	30	21	18	100	474 CD	200 A
60	Uttar Kannad	KA	0.58	0.97	1.7	294	0.6	11	30	7.9	18.3	80	86	4	7	10	389 C	286 B
61	Garhwal	UT	0.16	0.17	1.1	279	0.4	12	38	8.0	15.6	99	76	9	10	0	402 C	268 B
62	Darrang (Mangaldai)	AS	0.18	0.22	1.2	501	0.2	9	8	8.1	13.9	66	97	6	5	0	532 D	498 E
63	Parbhani	MA	0.79	0.67	0.9	274	0.3	17	96	8.1	12.4	60	35	10	14	97	565 D	249 B
64	Sonitpur (Tezpur)	AS	0.16	0.23	1.4	502	0.3	9	9	8.2	14.0	65	97	6	5	0	533 D	499 E
65	Jalgaon	MA	0.45	0.49	1.1	234	0.5	18	91	8.3	12.7	35	22	17	13	100	514 D	209 A
66	Bangalore Rural	KA	0.14	0.24	1.8	239	0.7	15	53	8.3	19.1	54	20	21	22	87	429 CD	221 A
67	Rajauri	JK	0.10	0.18	1.8	203	0.9	17	56	8.4	9.3	98	105	14	8	1	410 C	184 A
68	Sibsagar	AS	0.10	0.18	1.8	520	0.4	9	6	8.6	14.8	62	97	6	5	0	535 D	518 E
69	Almora	UT	0.14	0.15	1.1	248	0.4	13	32	8.7	16.8	93	76	9	11	0	363 C	237 B
70	Golaghat	AS	0.09	0.18	1.9	490	0.4	9	9	8.8	15.1	60	97	6	5	0	522 D	487 E
71	Kalahandi	OR	0.59	0.47	0.8	370	0.2	13	27	8.9	18.1	79	56	21	12	31	522 D	355 C
72	Dhemaji	AS	0.06	0.07	1.2	513	0.2	10	6	9.0	15.4	59	97	6	5	0	551 D	509 E
73	Amreli	GU	0.08	0.06	0.8	170	0.5	25	87	9.2	17.9	14	8	16	16	100	463 CD	140 A
74	Jorhat	AS	0.10	0.17	1.8	496	0.4	10	7	9.4	15.9	57	97	6	5	0	531 D	492 E
75	Tinsukia	AS	0.07	0.12	1.6	521	0.3	10	8	9.5	16.1	56	97	6	5	0	556 D	517 E
76	Pithoragarh	UT	0.08	0.10	1.2	237	0.5	14	36	9.5	18.1	76	76	7	10	0	338 C	226 B
77	Dibrugarh	AS	0.10	0.16	1.7	522	0.3	10	6	9.6	16.3	56	97	6	5	0	545 D	519 E
78	Chamba	HP	0.06	0.12	2.0	205	1.0	15	45	9.6	11.1	89	85	16	10	0	312 C	194 A
79	Wardha	MA	0.14	0.15	1.0	318	0.3	17	100	9.8	14.8	38	41	7	9	100	557 D	292 B
80	Chamoli	UT	0.05	0.06	1.3	214	0.6	15	40	10.3	19.5	74	76	7	10	0	315 C	202 A
81	Nagaur	RA	0.99	0.59	0.6	159	0.4	30	94	10.6	31.3	75	40	19	20	100	454 CD	124 A

(Continued)

Annex Table 1. Water productivity variations across districts in India (*Continued*).

ID	Districts[1]	State	Total and Irrigated area (Million ha), production (Million mt), CWU (km^3), NET and WP (kg/m^3) of grains															
			Total				Irrigation					Other data						
			Area	Production	Yield	CWU	WP	CWU - % of total CWU	NET - % of irri CWU	Area - % of total	Production - % of total	Grian area - % of GCA	Grian irri. area - % of GIA	NIA - % of NSA	GIA - % of GCA	GWIRA - % of GIA	CWU in irrigated grain area	CWU in rain-fed grain area
			M ha	M Mt	tonne/ha	mm	kg/m^3	%	%	%	%	%	%	%	%	%	mm	mm
82	Bhavnagar	GU	0.13	0.09	0.7	165	0.4	26	70	10.7	20.5	21	4	25	58	57	406 C	136 A
83	Doda	JK	0.07	0.08	1.1	154	0.7	23	69	10.7	11.9	84	96	12	9	0	329 C	134 A
84	Jaisalmer	RA	0.18	0.06	0.4	72	0.5	69	97	11.5	33.2	36	22	11	19	26	431 CD	25 A
85	Vidisha	MP	0.60	0.58	1.0	187	0.5	29	98	11.6	18.9	82	82	33	12	100	470 CD	150 A
86	Bikaner	RA	0.64	0.25	0.4	102	0.4	47	96	11.7	33.5	44	32	11	16	27	411 C	62 A
87	Godda	JH	0.08	0.09	1.1	370	0.3	10	81	11.7	17.6	85	69	13	14	39	312 C	377 C
88	Shimla	HP	0.05	0.07	1.6	224	0.7	17	35	11.7	13.5	44	88	5	6	0	318 C	211 A
89	Bankura	WB	0.43	1.10	2.6	451	0.6	12	38	11.9	15.6	75	54	62	16	100	467 CD	449 C
90	Vadodara	GU	0.39	0.27	0.7	261	0.3	24	65	12.3	23.3	73	32	35	28	100	507 D	227 B
91	Jalor	RA	0.41	0.19	0.5	166	0.3	38	91	12.9	36.1	55	29	34	25	100	488 D	119 A
92	Rajkot	GU	0.06	0.05	0.8	158	0.5	38	88	13.1	24.6	8	5	20	21	100	461 CD	112 A
93	N. Cacha Hills (Haflong)	AS	0.01	0.03	1.7	448	0.4	14	6	13.5	22.3	39	97	6	5	0	477 D	444 C
94	Panchmahals (Godhra)	GU	0.42	0.31	0.7	253	0.3	29	61	14.1	26.1	82	48	25	24	80	515 D	210 A
95	Tehri-Garhwal	UT	0.10	0.13	1.3	256	0.5	21	36	14.2	25.9	95	76	15	18	0	374 C	236 B
96	Chikmagalur	KA	0.10	0.19	1.8	324	0.6	23	49	14.2	30.1	44	51	8	12	22	517 D	292 B
97	Osmanabad	MA	0.63	0.35	0.6	244	0.2	25	62	14.7	21.7	79	73	21	16	56	408 C	216 A
98	Raj Nandgaon	CH	0.59	0.46	0.8	331	0.2	24	42	15.0	23.5	88	93	16	14	16	522 D	298 B
99	Guna	MP	0.64	0.58	0.9	206	0.4	34	98	15.1	23.9	79	88	20	14	100	459 CD	161 A
100	Punch	JK	0.05	0.09	1.8	181	1.0	33	68	15.3	16.9	98	90	14	17	0	389 C	143 A
101	Aurangabad	MA	0.61	0.49	0.8	275	0.3	24	62	15.6	22.9	60	57	21	17	100	415 C	249 B
102	Una	HP	0.06	0.11	1.6	237	0.7	25	41	15.7	18.0	88	85	21	16	84	377 C	211 A
103	Sangli	MA	0.47	0.34	0.7	233	0.3	30	73	16.3	23.8	68	48	21	23	71	433 CD	194 A
104	Alleppey	KE	0.03	0.08	2.2	467	0.5	19	30	16.4	20.9	27	15	45	29	18	544 D	452 C
105	Latur	MA	0.51	0.37	0.7	278	0.3	25	61	16.7	24.4	70	63	7	19	75	410 C	251 B
106	Sundargarh	OR	0.32	0.29	0.9	415	0.2	22	27	17.0	31.6	83	72	19	20	49	526 D	392 C
107	Nagpur	MA	0.23	0.21	0.9	324	0.3	28	70	17.2	25.0	40	41	19	16	86	531 D	281 B
108	Damoh	MP	0.35	0.23	0.7	260	0.3	30	95	17.3	27.0	84	93	30	16	68	445 CD	221 A

(Continued)

Annex Table 1. Water productivity variations across districts in India (*Continued*).

ID	Districts[1]	State	Total and Irrigated area (Million ha), production (Million mt), CWU (km^3), NET and WP (kg/m^3) of grains															
			Total					Irrigation				Other data						
			Area	Production	Yield	CWU	WP	CWU - % of total CWU	NET - % of irri CWU	Area - % of total	Production - % of total	Grian area - % of GCA	Grian irri. area - % of GIA	NIA - % of NSA	GIA - % of GCA	GWIRA - % of GIA	CWU in irrigated grain area	CWU in rain-fed grain area
			M ha	M Mt	tonne/ha	mm	kg/m^3	%	%	%	%	%	%	%	%	%	mm	mm
109	Jalna	MA	0.51	0.42	0.8	245	0.3	30	72	17.3	25.1	70	68	12	18	74	422 C	208 A
110	Solapur	MA	0.89	0.45	0.5	213	0.2	36	72	17.6	25.5	80	59	21	24	89	434 CD	166 A
111	Mandi	HP	0.14	0.30	2.1	263	0.8	23	30	17.8	20.3	85	88	17	17	0	345 C	246 B
112	Seoni	MP	0.32	0.16	0.5	260	0.2	34	73	17.8	27.7	74	91	22	15	43	505 D	207 A
113	Junagadh	GU	0.07	0.11	1.5	178	0.8	47	92	18.0	32.1	9	11	25	15	100	463CD	116 A
114	Sabarkantha (Himatnagar)	GU	0.31	0.35	1.1	247	0.5	39	85	18.4	32.8	61	28	41	40	100	521 D	185 A
115	Beed	MA	0.66	0.34	0.5	246	0.2	33	73	18.6	26.8	71	65	26	20	21	440 CD	201 A
116	Ajmer	RA	0.35	0.24	0.7	224	0.3	39	91	18.6	46.7	77	59	8	24	87	471 CD	168 A
117	Sidhi	MP	0.42	0.26	0.6	279	0.2	26	91	19.3	29.8	90	96	15	18	39	373 C	257 B
118	Jabalpur	MP	0.53	0.42	0.8	268	0.3	32	91	19.3	29.8	90	92	33	19	87	445 CD	226 B
119	Ratlam	MP	0.12	0.17	1.5	244	0.6	42	99	19.5	30.0	27	38	11	14	100	522 D	176 A
120	Mayurbhanj	OR	0.39	0.44	1.1	447	0.2	22	16	19.5	35.4	83	83	20	20	23	503 D	434 C
121	Jhunjhunun	RA	0.42	0.33	0.8	190	0.4	41	92	19.7	48.4	69	43	47	32	100	395 C	140 A
122	Rajgarh	MP	0.18	0.13	0.7	245	0.3	40	99	19.9	30.5	33	46	24	15	100	498 D	182 A
123	Betul	MP	0.19	0.21	1.1	298	0.4	35	100	19.9	30.6	41	64	23	13	100	525 D	242 B
124	Surendranagar	GU	0.09	0.12	1.3	199	0.6	55	97	20.1	35.2	17	15	18	23	100	543 D	112 A
125	West Nimar (Khargon)	MP	0.19	0.18	1.0	259	0.4	43	98	20.2	30.9	32	30	25	21	100	553 D	185 A
126	Udaipur	RA	0.35	0.45	1.3	321	0.4	32	94	20.4	49.5	75	66	24	23	54	501 D	275 B
127	Chhindwara	MP	0.27	0.39	1.4	279	0.5	37	99	20.5	31.4	51	65	16	16	100	501 D	222 A
128	Adilabad	AP	0.37	0.48	1.3	331	0.4	37	53	20.5	47.6	64	73	14	18	38	588 D	264 B
129	Dhenkanal	OR	0.40	0.30	0.7	412	0.2	27	22	20.7	37.0	68	72	23	19	38	538 D	379 C
130	Koraput	OR	0.73	0.78	1.1	408	0.3	26	18	20.8	37.2	68	65	25	22	34	504 D	383 C
131	Bijapur	KA	0.69	0.62	0.9	209	0.4	44	75	21.0	40.9	57	41	29	29	50	433 CD	149 A
132	Uttarkashi	UT	0.04	0.05	1.4	124	1.1	42	67	21.1	36.1	83	76	15	23	0	246 B	91 A
133	Kendujhar	OR	0.30	0.21	0.7	413	0.2	26	20	21.2	37.7	79	81	22	20	26	509 D	387 C
134	Shajapur	MP	0.16	0.20	1.3	252	0.5	43	98	21.6	32.8	25	53	23	10	100	496 D	184 A
135	Pune	MA	0.88	0.62	0.7	270	0.3	32	62	21.7	30.8	76	64	25	26	58	395 C	235 B

(Continued)

Annex Table 1. Water productivity variations across districts in India (*Continued*).

ID	Districts[1]	State	Total and Irrigated area (Million ha), production (Million mt), CWU (km^3), NET and WP (kg/m^3) of grains														
			Total					Irrigation				Other data					
			Area	Production	Yield	CWU	WP	CWU - % of total CWU	NET - % of irri CWU	Area - % of total	Production - % of total	Grian area - % of GCA	Grian irri. area - % of GIA	NIA - % of NSA	GIA - % of GCA	GWIRA - % of GIA	CWU in irrigated grain area	CWU in rain-fed grain area
			M ha	M Mt	tonne/ha	mm	kg/m^3	%	%	%	%	%	%	%	%	%	mm	mm
136	Coimbatore	TN	0.15	0.13	0.9	317	0.3	31	38	22.5	47.3	45	19	55	53	79	442 CD	281 B
137	Rangareddi	AP	0.23	0.26	1.1	323	0.4	45	66	22.6	50.7	71	65	26	25	89	640 D	231 B
138	Solan	HP	0.06	0.10	1.7	264	0.6	29	35	22.7	25.7	89	76	26	27	8	332 C	244 B
139	Dungarpur	RA	0.14	0.14	1.0	331	0.3	36	92	23.0	53.4	94	76	21	28	33	522 D	274 B
140	East Nimar (Khandwa)	MP	0.12	0.10	0.9	306	0.3	42	99	23.1	34.7	25	35	25	17	100	550 D	233 B
141	Narsimhapur	MP	0.35	0.54	1.5	298	0.5	37	99	23.4	35.0	72	77	54	22	100	476 D	244 B
142	Sikar	RA	0.48	0.54	1.1	210	0.5	46	94	23.4	53.9	72	53	42	32	100	413 C	148 A
143	Chidambaranar	TN	0.07	0.11	1.8	194	0.9	71	85	24.0	49.4	39	38	22	24	50	573 D	74 A
144	Phulbani	OR	0.20	0.20	1.0	391	0.3	32	24	24.0	41.6	72	76	21	23	24	516 D	351 C
145	Raisen	MP	0.46	0.43	0.9	268	0.3	45	100	24.0	35.9	80	94	30	21	81	500 D	195 A
146	Dharwad	KA	0.58	0.83	1.4	237	0.6	46	69	24.0	45.2	48	62	18	19	36	454 CD	169 A
147	Ahmadnagar	MA	1.01	0.54	0.5	209	0.3	50	80	24.5	34.2	68	62	25	27	73	429 CD	137 A
148	Kinnaur	HP	0.00	0.00	1.1	185	0.6	30	49	25.1	28.3	42	17	65	60	0	220 A	173 A
149	Kachchh (Bhuj)	GU	0.20	0.12	0.6	162	0.4	73	92	25.1	42.1	33	22	18	38	82	471 CD	59 A
150	Tumkur	KA	0.25	0.38	1.5	232	0.7	57	78	25.2	46.7	43	44	23	25	73	523 D	134 A
151	Rewa	MP	0.50	0.39	0.8	262	0.3	36	91	25.2	37.4	94	100	23	24	47	379 C	223 A
	Total or average (% grain irrigated area <25%)																	
	CWU < 225 mm	38	14.3	9.7	1.01	176	0.58	30	86	12	25	60	37	19	19	78	424	140
	225mm < CWU < 300 mm	47	17.1	16.2	1.04	260	0.40	25	79	15	25	34	28	19	16	74	453	228
	225mm < CWU < 475 mm	48	11.9	14.0	1.30	387	0.34	15	43	11	19	17	12	16	14	49	472	371
	475 mm < CWU	19	2.4	3.6	1.52	499	0.30	8	7	8	13	70	97	6	5	0	525	497
	Total or average	152	45.8	43.5	1.17	309	0.41	21	69	12	22	31	23	16	16	69	461	285
152	Bahraich	UP	0.66	1.15	1.7	297	0.6	24	88	25	44	91	87	35	27	83	279 B	303 C
153	Dhar	MP	0.17	0.16	1.0	274	0.4	52	99	26	38	28	40	20	18	100	557 D	176 A
154	Kollam (Quilon)	KE	0.01	0.03	2.3	439	0.5	32	36	26	32	6	40	1	4	35	540 D	405 C
155	Pathanamthitta	KE	0.01	0.01	2.5	430	0.6	32	34	26	32	5	50	5	2	32	517 D	399 C
156	Chandrapur	MA	0.32	0.31	1.0	368	0.3	40	42	26	36	61	82	22	19	25	562 D	299 B

(Continued)

Annex Table 1. Water productivity variations across districts in India (*Continued*).

ID	Districts[1]	State	Total and Irrigated area (Million ha), production (Million mt), CWU (km^3), NET and WP (kg/m^3) of grains															
			Total					Irrigation				Other data						
			Area	Production	Yield	CWU	WP	CWU - % of total CWU	NET - % of irri CWU	Area - % of total	Production - % of total	Grian area - % of GCA	Grian irri. area - % of GIA	NIA - % of NSA	GIA - % of GCA	GWIRA - % of GIA	CWU in irrigated grain area	CWU in rain-fed grain area
			M ha	M Mt	tonne/ha	mm	kg/m^3	%	%	%	%	%	%	%	%	%	mm	mm
157	Mahbubnagar	AP	0.55	0.50	0.9	324	0.3	53	69	26	56	59	61	20	26	78	653 D	206 A
158	Dharmapuri	TN	0.29	0.49	1.7	285	0.6	51	61	27	53	60	50	33	32	60	548 D	190 A
159	Quaide Milleth	TN	0.13	0.27	2.1	288	0.7	46	55	27	53	50	33	39	40	80	495 D	213 A
160	Birbhum (Situri)	WB	0.41	1.10	2.7	436	0.6	28	41	27	34	82	54	119	41	10	449 CD	431 C
161	Palamu (Daltenganj)	JH	0.23	0.21	0.9	365	0.2	38	33	28	38	71	81	27	24	38	497 D	315 C
162	Tonk	RA	0.29	0.22	0.8	268	0.3	48	91	28	60	50	52	42	27	90	456 CD	195 A
163	Mandsaur	MP	0.22	0.31	1.4	255	0.5	51	96	28	41	29	50	26	16	100	457 CD	176 A
164	Kolar	KA	0.15	0.26	1.7	277	0.6	47	59	29	51	47	43	22	31	89	453 CD	205 A
165	Medak	AP	0.41	0.52	1.3	363	0.3	51	61	29	59	74	60	29	36	67	641 D	249 B
166	Satara	MA	0.46	0.45	1.0	275	0.4	41	48	29	40	67	60	29	32	72	383 C	231 B
167	Pali	RA	0.34	0.22	0.6	257	0.3	58	93	30	62	55	55	26	30	70	497 D	154 A
168	West Dinajpur	WB	0.56	1.15	2.1	441	0.5	29	41	30	37	75	80	6	28	55	432 CD	445 C
169	Bilaspur	CH	0.85	0.91	1.1	379	0.3	40	39	30	43	93	90	33	31	10	508 D	323 C
170	Kangra	HP	0.20	0.31	1.5	278	0.5	39	29	30	34	91	88	31	31	0	358 C	244 B
171	Dakshin Kannad	KA	0.13	0.25	1.9	478	0.4	35	40	30	53	56	46	45	37	48	557 D	443 C
172	Mahendragarh	HA	0.17	0.32	1.9	244	0.8	42	90	32	63	62	41	81	48	100	321 C	208 A
173	Kozhikode	KE	0.01	0.01	1.3	409	0.3	43	48	32	39	3	61	3	2	100	548 D	343 C
174	Banda	UP	0.60	0.72	1.2	293	0.4	46	70	32	52	95	97	31	32	29	417 C	235 B
175	Sirmaur (Nahan)	HP	0.07	0.12	1.9	271	0.7	42	38	32	36	83	79	37	34	17	355 C	232 B
176	Kupwara (Gilgit Wazarat)	JK	0.04	0.04	1.0	177	0.5	85	92	32	35	84	69	42	39	0	466 CD	39 A
177	Bhilwara	RA	0.37	0.49	1.3	323	0.4	49	94	33	65	77	60	41	42	65	488 D	243 B
178	Balangir	OR	0.46	0.56	1.2	429	0.3	42	29	33	52	82	84	24	32	25	550 D	370 C
179	Valsad	GU	0.16	0.36	2.3	396	0.6	48	46	33	51	51	34	41	49	60	578 D	306 C
180	Thiruvananthapuram (Triv)	KE	0.01	0.02	2.0	394	0.5	45	45	33	40	4	75	3	2	20	538 D	323 C
181	Hamirpur	UP	0.55	0.62	1.1	249	0.5	35	87	33	53	88	92	33	32	50	261 B	244 B
182	Sagar	MP	0.50	0.30	0.6	232	0.3	56	93	33	47	74	95	32	26	59	393 C	153 A
183	Sehore	MP	0.20	0.27	1.3	302	0.4	58	99	34	47	38	68	45	19	100	519 D	192 A

(Continued)

Annex Table 1. Water productivity variations across districts in India (*Continued*).

			Total and Irrigated area (Million ha), production (Million mt), CWU (km^3), NET and WP (kg/m^3) of grains															
			Total					Irrigation				Other data						
ID	Districts[1]	State	Area	Production	Yield	CWU	WP	CWU - % of total CWU	NET - % of irri CWU	Area - % of total	Production - % of total	Grian area - % of GCA	Grian irri. area - % of GIA	NIA - % of NSA	GIA - % of GCA	GWIRA - % of GIA	CWU in irrigated grain area	CWU in rain-fed grain area
			M ha	M Mt	tonne/ha	mm	kg/m^3	%	%	%	%	%	%	%	%	%	mm	mm
184	Gonda	UP	0.65	1.26	1.9	317	0.6	29	91	34	54	82	75	57	37	96	272 B	340 C
185	Kishanganj	BI	0.11	0.13	1.2	434	0.3	33	26	34	48	64	78	26	28	87	412 C	445 C
186	Chitradurga	KA	0.48	1.16	2.4	249	1.0	71	80	35	58	55	64	26	30	48	507 D	110 A
187	Hassan	KA	0.19	0.34	1.8	336	0.5	54	52	35	58	55	71	21	27	22	514 D	241 B
188	Belgaum	KA	0.43	0.53	1.2	281	0.4	54	70	35	59	47	37	45	45	43	430 CD	201 A
189	Durg	CH	0.65	0.60	0.9	374	0.2	49	44	35	49	89	93	35	34	21	521 D	295 B
190	Banswara	RA	0.27	0.28	1.0	378	0.3	47	87	35	67	95	87	29	38	10	509 D	307 C
191	Surat	GU	0.18	0.36	2.0	367	0.5	55	55	35	54	39	20	49	72	27	573 D	254 B
192	Dewas	MP	0.13	0.14	1.1	327	0.3	59	99	35	49	25	58	30	15	100	545 D	207 A
193	Ganjam	OR	0.60	0.35	0.6	407	0.1	47	24	36	56	79	83	43	34	17	533 D	337 C
194	Kurnool	AP	0.29	0.45	1.5	328	0.5	67	75	36	66	31	41	20	27	43	613 D	170 A
195	Baleshwar	OR	0.48	0.44	0.9	494	0.2	38	13	36	56	85	83	43	37	39	527 D	476 E
196	Sitamarhi	BI	0.21	0.24	1.2	346	0.3	32	71	36	49	79	89	34	32	74	304 C	370 C
197	Chittaurgarh	RA	0.30	0.49	1.7	370	0.4	49	93	37	69	57	56	37	37	79	496 D	297 B
198	Raichur	KA	0.61	0.91	1.5	307	0.5	69	78	37	61	60	62	24	36	20	567 D	153 A
199	Raipur	CH	1.06	1.21	1.1	393	0.3	49	40	37	51	95	89	46	40	11	512 D	321 C
200	Banas Kantha	GU	0.40	0.45	1.1	265	0.4	70	89	37	56	44	50	43	33	100	497 D	127 A
201	Madhubani	BI	0.25	0.30	1.2	367	0.3	35	61	39	52	85	92	37	36	37	331 C	390 C
202	Satna	MP	0.48	0.25	0.5	240	0.2	52	86	39	53	93	100	31	37	49	316C	191 A
203	Ramanathapuram	TN	0.13	0.17	1.3	318	0.4	81	83	40	67	72	81	37	36	22	643 D	101 A
204	Kathua	JK	0.11	0.17	1.5	309	0.5	57	36	40	43	89	105	35	34	1	436 CD	224 A
205	Panna	MP	0.30	0.15	0.5	247	0.2	49	81	40	54	97	99	24	39	15	302 C	210 A
206	Mysore	KA	0.33	0.60	1.8	359	0.5	57	50	40	64	61	72	28	34	25	510 D	257 B
207	Bhopal	MP	0.14	0.16	1.2	308	0.4	66	99	40	55	59	89	40	27	94	499 D	178 A
208	Darbhanga	BI	0.22	0.27	1.2	356	0.3	38	65	41	54	98	100	37	40	25	331 C	373 C
209	Cuttack	OR	0.79	0.40	0.5	472	0.1	48	16	41	61	79	82	62	40	19	546 D	420 C
210	Puri	OR	0.61	0.42	0.7	466	0.1	49	18	42	62	85	91	57	39	24	552 D	404 C

(Continued)

Annex Table 1. Water productivity variations across districts in India (*Continued*).

ID	Districts[1]	State	Total and Irrigated area (Million ha), production (Million mt), CWU (km^3), NET and WP (kg/m^3) of grains															
			Total					Irrigation				Other data						
			Area	Production	Yield	CWU	WP	CWU - % of total CWU	NET - % of irri CWU	Area - % of total	Production - % of total	Grian area - % of GCA	Grian irri. area - % of GIA	NIA - % of NSA	GIA - % of GCA	GWIRA - % of GIA	CWU in irrigated grain area	CWU in rain-fed grain area
			M ha	M Mt	tonne/ha	mm	kg/m^3	%	%	%	%	%	%	%	%	%	mm	mm
211	Garhchiroli	MA	0.18	0.17	1.0	434	0.2	52	34	42	53	96	100	31	40	3	540 D	359 C
212	Muzaffarpur	BI	0.26	0.44	1.7	320	0.5	40	72	42	55	86	86	46	42	78	306 C	330 C
213	Siddharthnagar	UP	0.30	0.60	2.0	346	0.6	32	94	42	62	88	87	56	42	79	260 B	408 C
214	Jalaun	UP	0.36	0.71	2.0	274	0.7	45	91	42	63	91	95	43	40	27	295 B	258 B
215	Sambalpur	OR	0.66	1.22	1.8	467	0.4	50	26	42	62	77	86	32	38	18	545 D	408 C
216	Balaghat	MP	0.34	0.34	1.0	380	0.3	58	43	43	57	98	97	49	43	15	518 D	277 B
217	Sonbhadra	UP	0.24	0.34	1.4	355	0.4	56	48	43	63	87	96	27	39	2	459 CD	276 B
218	Dehra Dun	UT	0.06	0.11	1.7	279	0.6	62	40	43	62	81	76	79	46	0	406 C	184 A
219	Salem	TN	0.17	0.38	2.3	320	0.7	73	65	43	70	43	42	45	44	100	537 D	154 A
220	South 24 Panganas	WB	0.45	0.95	2.1	476	0.4	45	26	44	52	78	93	28	37	5	480 D	474 C
221	North 24 Panganas	WB	0.34	0.82	2.5	460	0.5	45	29	45	52	63	79	14	35	100	462 CD	458 C
222	Sawai Madhopur	RA	0.35	0.50	1.4	291	0.5	66	92	45	76	61	57	57	48	85	423 C	181 A
223	Bellary	KA	0.27	0.53	1.9	296	0.7	78	79	46	69	54	58	32	43	27	505 D	122 A
224	Kannur (Cannanore)	KE	0.01	0.02	1.8	440	0.4	58	49	46	53	5	61	9	3	100	553 D	343 C
225	Samastipur	BI	0.22	0.39	1.8	322	0.6	46	66	46	60	85	91	40	43	87	322 C	322 C
226	Vaishali	BI	0.15	0.27	1.8	311	0.6	47	70	46	60	74	81	51	42	96	313 C	309 C
227	Maharajganj	UP	0.32	0.73	2.3	361	0.6	36	84	47	67	88	86	73	48	76	280 B	433 C
228	Kasaragod	KE	0.01	0.02	2.1	452	0.5	58	47	47	54	5	27	34	9	100	556 D	360 C
229	Jhalawar	RA	0.15	0.20	1.3	362	0.4	61	92	47	77	35	44	53	38	94	474 CD	263 B
230	Jaipur	RA	0.74	1.21	1.6	290	0.6	69	92	47	77	66	56	60	55	92	426 CD	168 A
231	Khammam	AP	0.25	0.49	1.9	463	0.4	62	48	47	76	57	63	38	43	35	612 D	329 C
232	Wayanad (Wynad)	KE	0.01	0.03	2.5	411	0.6	58	46	48	55	7	50	4	6	0	500 D	329 C
233	Bhagalpur	BI	0.35	0.53	1.5	344	0.4	57	40	48	62	94	91	49	50	55	409 C	283 B
234	Araria	BI	0.19	0.27	1.4	375	0.4	44	50	49	62	76	86	35	43	43	338 C	410 C
235	Paschim Champaran	BI	0.33	0.64	1.9	387	0.5	49	42	49	62	86	90	43	47	78	387 C	387 C
236	Kamarajar	TN	0.07	0.15	2.2	348	0.6	80	72	49	75	45	53	41	42	61	568 D	135 A
237	Sirohi	RA	0.09	0.11	1.3	360	0.4	67	85	49	79	49	65	37	38	91	486 D	238 B

(Continued)

Annex Table 1. Water productivity variations across districts in India (*Continued*).

			Total and Irrigated area (Million ha), production (Million mt), CWU (km^3), NET and WP (kg/m^3) of grains															
			Total					Irrigation				Other data						
ID	Districts[1]	State	Area	Production	Yield	CWU	WP	CWU - % of total CWU	NET - % of irri CWU	Area - % of total	Production - % of total	Grian area - % of GCA	Grian irri. area - % of GIA	NIA - % of NSA	GIA - % of GCA	GWIRA - % of GIA	CWU in irrigated grain area	CWU in rain-fed grain area
			M ha	M Mt	tonne/ha	mm	kg/m^3	%	%	%	%	%	%	%	%	%	mm	mm
238	Jhansi	UP	0.37	0.58	1.6	267	0.6	56	90	49	69	83	95	55	43	47	300 C	233 B
239	Basti	UP	0.44	0.96	2.2	338	0.6	42	88	50	70	89	83	67	54	89	284 B	392 C
240	Idukki	KE	0.01	0.01	2.4	429	0.6	57	32	50	58	2	23	6	4	4	488 D	369 C
241	North Arcot (Ambedkar)	TN	0.19	0.48	2.5	410	0.6	77	63	50	76	36	39	43	47	53	630 D	188 A
242	Siwan	BI	0.25	0.42	1.7	324	0.5	47	83	51	64	93	91	61	52	70	296 B	353 C
243	Saran	BI	0.23	0.42	1.8	332	0.5	47	81	51	64	97	99	45	50	64	302 C	363 C
244	Gopalganj	BI	0.22	0.42	1.9	335	0.6	45	82	52	65	91	93	59	50	43	294 B	378 C
245	Murshidabad	WB	0.52	1.23	2.4	391	0.6	53	53	52	60	64	81	40	41	100	403 C	377 C
246	Rewari	HA	0.11	0.30	2.7	268	1.0	61	94	52	80	57	42	78	70	100	313 C	219 A
247	Tiruchchirappalli	TN	0.28	0.67	2.4	433	0.6	79	74	52	77	53	58	46	47	60	656 D	191 A
248	Ujjain	MP	0.09	0.10	1.0	344	0.3	75	98	52	66	13	61	17	11	86	497 D	178 A
249	Kottayam	KE	0.02	0.04	2.3	484	0.5	59	33	53	60	8	78	9	5	7	542 D	419 C
250	Jammu	JK	0.18	0.24	1.3	300	0.4	77	46	53	56	91	100	49	48	0	438 CD	147 A
251	Munger	BI	0.30	0.35	1.2	353	0.3	58	53	53	66	96	92	59	55	31	389 C	312 C
252	Agra	UP	0.27	0.59	2.2	287	0.8	54	91	53	72	62	58	81	56	89	293 B	281 B
253	Gandhinagar	GU	0.03	0.09	2.8	342	0.8	87	75	53	71	51	47	60	58	100	565 D	91 A
254	Vishakhapatnam	AP	0.14	0.18	1.3	462	0.3	66	48	53	80	36	45	30	42	8	571 D	337 C
255	Bhandara	MA	0.40	0.46	1.2	445	0.3	65	40	54	65	72	93	50	42	22	541 D	334 C
256	Baramula (Kashmir North)	JK	0.06	0.07	1.1	299	0.4	90	87	54	57	66	70	48	51	2	501 D	63 A
257	Bhiwani	HA	0.39	0.70	1.8	249	0.7	72	87	54	81	57	53	59	58	42	331 C	153 A
258	Gorakhpur	UP	0.36	0.77	2.1	334	0.6	46	87	54	73	94	91	78	56	94	284 B	393 C
259	Prakasam	AP	0.32	0.65	2.0	441	0.5	80	73	55	81	55	75	38	40	36	644 D	196 A
260	Purnia	BI	0.20	0.34	1.7	364	0.5	50	55	55	68	69	73	57	52	68	330 C	405 C
261	Purbi Champaran	BI	0.33	0.54	1.6	358	0.5	56	53	55	68	80	87	55	50	17	361 C	354 C
262	Indore	MP	0.11	0.14	1.3	379	0.3	79	99	56	69	27	69	29	21	100	538 D	181 A
263	Lalitpur	UP	0.32	0.34	1.1	266	0.4	65	87	56	74	90	99	70	51	43	309 C	212 A
264	Alwar	RA	0.43	0.78	1.8	298	0.6	74	91	56	83	59	53	86	62	100	395 C	176 A

(Continued)

Annex Table 1. Water productivity variations across districts in India (*Continued*).

			Total and Irrigated area (Million ha), production (Million mt), CWU (km^3), NET and WP (kg/m^3) of grains															
			Total					Irrigation			Other data							
ID	Districts[1]	State	Area	Production	Yield	CWU	WP	CWU - % of total CWU	NET - % of irri CWU	Area - % of total	Production - % of total	Grian area - % of GCA	Grian irri. area - % of GIA	NIA - % of NSA	GIA - % of GCA	GWIRA - % of GIA	CWU in irrigated grain area	CWU in rain-fed grain area
			M ha	M Mt	tonne/ha	mm	kg/m^3	%	%	%	%	%	%	%	%	%	mm	mm
265	Srikakulam	AP	0.28	0.44	1.6	459	0.3	73	57	56	82	67	79	57	48	7	591 D	288 B
266	Guntur	AP	0.61	1.34	2.2	466	0.5	79	70	56	82	71	80	60	50	11	656 D	220 A
267	Khagaria	BI	0.12	0.23	2.0	305	0.6	62	60	56	69	86	83	71	58	97	334 C	268 B
268	Mahesana	GU	0.26	0.40	1.5	350	0.4	82	89	56	74	37	45	53	47	100	510 D	144 A
269	Malappuram	KE	0.02	0.05	2.0	460	0.4	66	45	56	64	9	33	13	16	42	541 D	356 C
270	Periyar	TN	0.11	0.31	2.7	362	0.7	87	78	57	80	34	33	55	58	54	560 D	104 A
271	Barddhaman	WB	0.65	1.82	2.8	465	0.6	59	31	58	65	75	80	96	54	41	479 D	448 C
272	Bagdam	JK	0.04	0.05	1.2	343	0.4	87	80	58	61	77	69	60	64	0	519 D	103 A
273	Maldah	WB	0.31	0.69	2.3	397	0.6	61	42	58	66	69	87	9	46	94	417 C	369 C
274	Ahmadabad	GU	0.24	0.27	1.1	389	0.3	90	77	59	75	47	81	29	34	100	595 D	96 A
275	Vizianagaram	AP	0.17	0.25	1.5	483	0.3	71	48	59	84	38	65	37	34	11	582 D	341 C
276	Begusarai	BI	0.16	0.25	1.6	283	0.6	66	71	59	71	86	94	59	54	80	315 C	238 B
277	Hugli (Chunchura)	WB	0.28	0.72	2.6	468	0.6	61	30	59	67	54	79	80	41	100	478 D	455 C
278	Palakkad (Palghat)	KE	0.13	0.29	2.3	466	0.5	70	43	61	67	40	47	37	51	12	535 D	360 C
279	Mandya	KA	0.15	0.33	2.2	382	0.6	81	69	61	80	62	69	43	54	13	508 D	187 A
280	Shimoga	KA	0.18	0.41	2.3	465	0.5	71	49	62	81	78	74	61	65	10	537 D	348 C
281	Warangal	AP	0.33	0.70	2.1	489	0.4	79	54	62	85	54	60	62	56	78	625 D	268 B
282	Bangalore Urban	KA	0.07	0.11	1.6	435	0.4	80	66	63	82	80	91	20	56	27	551 D	239 B
283	Bhind	MP	0.21	0.18	0.9	317	0.3	73	87	63	75	64	97	35	41	62	367 C	230 B
284	Patna	BI	0.18	0.39	2.1	433	0.5	79	30	63	75	76	68	66	71	100	537 D	252 B
285	Nadia (Krishnanagar)	WB	0.41	0.99	2.4	411	0.6	68	39	64	70	55	78	5	45	100	440 CD	361 C
286	Anantapur	AP	0.14	0.25	1.8	421	0.4	88	80	64	86	11	50	14	14	61	585 D	133 A
287	Farrukhabad	UP	0.32	0.79	2.5	296	0.8	72	76	64	80	69	64	85	68	97	336 C	226 B
288	Nalgonda	AP	0.36	0.63	1.7	503	0.3	84	70	64	86	60	83	40	46	55	665 D	217 A
289	East Godavari	AP	0.57	1.36	2.4	500	0.5	78	52	64	86	75	84	64	58	25	610 D	302 C
290	Kanpur Dehat	UP	0.28	0.66	2.4	351	0.7	73	70	65	81	86	86	69	64	47	398 C	266 B
291	Mirzapur	UP	0.29	0.53	1.8	385	0.5	70	62	65	81	91	97	61	61	25	418 C	326 C

(Continued)

Annex Table 1. Water productivity variations across districts in India (*Continued*).

			Total and Irrigated area (Million ha), production (Million mt), CWU (km^3), NET and WP (kg/m^3) of grains															
			Total					Irrigation				Other data						
ID	Districts[1]	State	Area	Production	Yield	CWU	WP	CWU - % of total CWU	NET - % of irri CWU	Area - % of total	Production - % of total	Grian area - % of GCA	Grian irri. area - % of GIA	NIA - % of NSA	GIA - % of GCA	GWIRA - % of GIA	CWU in irrigated grain area	CWU in rain-fed grain area
			M ha	M Mt	tonne/ha	mm	kg/m^3	%	%	%	%	%	%	%	%	%	mm	mm
292	Fatehpur	UP	0.37	0.71	1.9	374	0.5	74	67	65	81	87	89	63	63	76	428 CD	275 B
293	Bharatpur	RA	0.28	0.62	2.2	311	0.7	81	91	65	88	54	58	74	61	92	389 C	168 A
294	Ballia	UP	0.32	0.62	1.9	346	0.6	72	60	65	81	90	88	74	66	79	381 C	280 B
295	Medinipur	WB	1.13	2.64	2.3	483	0.5	67	30	65	72	79	90	53	57	44	493 D	464 C
296	Kandur Nagar	UP	0.23	0.51	2.2	344	0.6	74	71	65	81	75	81	74	61	61	387 C	263 B
297	Deoria	UP	0.52	1.19	2.3	358	0.6	63	64	65	81	79	85	73	61	64	344 C	384 C
298	Kheda	GU	0.35	0.55	1.6	427	0.4	86	71	66	80	62	70	59	58	80	557 D	179 A
299	Firozabad	UP	0.23	0.50	2.2	313	0.7	69	77	66	82	80	77	94	69	89	329 C	280 B
300	Krishna	AP	0.55	1.23	2.2	510	0.4	83	59	66	87	78	81	67	64	14	639 D	256 B
301	Nizamabad	AP	0.32	0.69	2.1	482	0.4	82	55	67	88	80	73	68	74	48	595 D	256 B
302	Sitapur	UP	0.44	0.82	1.8	360	0.5	72	62	67	82	70	72	54	65	83	387 C	305 C
303	Morena	MP	0.22	0.43	2.0	354	0.6	82	95	68	79	47	87	60	37	100	424 C	201 A
304	Saharsa	BI	0.36	0.49	1.4	375	0.4	65	49	69	79	77	89	63	59	55	356 C	416 C
305	Budaun	UP	0.57	1.22	2.1	331	0.6	73	74	69	83	84	80	85	72	99	352 C	284 B
306	Daulpur	RA	0.09	0.22	2.5	322	0.8	83	90	69	89	48	58	66	58	79	388 C	176 A
307	Allahabad	UP	0.66	1.22	1.8	396	0.5	77	62	69	84	87	89	68	68	51	439 CD	298 B
308	Sultanpur	UP	0.38	0.84	2.2	377	0.6	73	63	69	84	86	88	75	68	68	395 C	335 C
309	Madurai	TN	0.15	0.49	3.2	443	0.7	85	56	69	88	54	62	58	60	58	543 D	216 A
310	Azamgarh	UP	0.46	0.97	2.1	365	0.6	70	66	70	84	89	87	90	72	82	369 C	356 C
311	Anantnag (Kashmir South)	JK	0.07	0.08	1.2	369	0.3	90	75	70	72	65	62	62	73	0	475 CD	122 A
312	Gurgaon	HA	0.20	0.53	2.6	299	0.9	78	87	70	89	66	66	46	70	72	331 C	223 A
313	Maij	UP	0.19	0.40	2.1	365	0.6	70	65	70	84	88	87	89	72	91	366 C	364 C
314	Shivpuri	MP	0.34	0.39	1.1	306	0.4	80	91	70	81	63	96	37	47	60	349 C	204 A
315	Madhepura	BI	0.17	0.35	2.0	369	0.6	67	47	70	81	76	88	76	61	50	350 C	413 C
316	Tiruvannamalai Sambuvaray	TN	0.16	0.37	2.4	546	0.4	89	62	72	89	55	55	62	71	82	674 D	221 A
317	Kota	RA	0.27	0.56	2.1	382	0.5	88	87	72	91	33	42	79	57	61	464 CD	170 A
318	Bhojpur	BI	0.42	0.88	2.1	384	0.5	85	50	73	82	94	84	82	82	21	448 CD	209 A

(Continued)

Annex Table 1. Water productivity variations across districts in India (*Continued*).

ID	Districts[1]	State	Total and Irrigated area (Million ha), production (Million mt), CWU (km^3), NET and WP (kg/m^3) of grains															
			Total					Irrigation			Other data							
			Area	Production	Yield	CWU	WP	CWU - % of total CWU	NET - % of irri CWU	Area - % of total	Production - % of total	Grian area - % of GCA	Grian irri. area - % of GIA	NIA - % of NSA	GIA - % of GCA	GWIRA - % of GIA	CWU in irrigated grain area	CWU in rain-fed grain area
			M ha	M Mt	tonne/ha	mm	kg/m^3	%	%	%	%	%	%	%	%	%	mm	mm
319	Gangangar	RA	0.84	1.54	1.8	294	0.6	94	97	73	91	44	54	58	59	1	378 C	63 A
320	Kheri	UP	0.43	1.08	2.5	378	0.7	80	51	74	86	59	63	72	69	90	411 C	286 B
321	Etawah	UP	0.40	0.96	2.4	371	0.6	81	68	74	87	86	87	82	72	55	408 C	271 B
322	South Arcot	TN	0.38	1.12	2.9	570	0.5	90	67	74	90	57	67	63	63	72	692 D	222 A
323	Jaunpur	UP	0.41	0.83	2.0	368	0.6	82	63	75	87	90	89	78	75	68	403 C	264 B
324	Thanjavur	TN	0.69	1.75	2.6	557	0.5	95	75	75	90	88	90	88	73	29	708 D	108 A
325	Karimnagar	AP	0.43	1.17	2.7	516	0.5	87	56	75	91	79	76	72	78	68	601 D	263 B
326	Etah	UP	0.44	1.00	2.3	320	0.7	79	71	75	87	85	84	88	76	85	338 C	265 B
327	Pulwama	JK	0.04	0.05	1.4	409	0.3	93	75	76	78	48	52	62	69	0	500 D	124 A
328	Hardoi	UP	0.57	1.17	2.1	350	0.6	82	69	76	88	85	90	79	71	80	380 C	258 B
329	Rohtas	BI	0.61	1.32	2.2	410	0.5	87	47	76	84	98	89	98	84	26	470 CD	220 A
330	Gaya	BI	0.25	0.38	1.5	431	0.4	85	40	76	85	97	100	65	74	44	481 D	270 B
331	Barabanki	UP	0.35	0.76	2.2	407	0.5	83	54	77	88	77	76	84	78	68	439 CD	304 C
332	Aligarh	UP	0.61	1.46	2.4	316	0.8	80	73	77	89	80	79	99	79	86	329 C	271 B
333	Gwalior	MP	0.20	0.38	1.9	369	0.5	87	80	77	86	84	98	72	66	45	416 C	210 A
334	Unnao	UP	0.39	0.76	1.9	359	0.5	85	70	77	89	88	89	88	76	78	392 C	243 B
335	Cuddapah	AP	0.11	0.21	1.9	553	0.4	93	78	77	92	25	48	40	40	76	663 D	176 A
336	Nainital	UT	0.28	0.76	2.7	391	0.7	86	40	77	88	79	76	83	81	0	433 CD	244 B
337	Pasumpon Muthuramalingam	TN	0.09	0.18	2.2	542	0.4	92	67	78	92	73	83	70	69	25	636 D	206 A
338	Partapgarh	UP	0.32	0.60	1.8	395	0.5	83	63	78	89	94	96	80	77	59	421 C	303 C
339	Nellore	AP	0.29	0.74	2.6	586	0.4	94	78	78	93	77	70	73	86	34	702 D	167 A
340	Tikamgarh	MP	0.22	0.32	1.4	356	0.4	85	93	78	86	53	93	75	45	91	384 C	252 B
341	Katihar	BI	0.19	0.32	1.7	395	0.4	87	28	79	86	68	89	63	60	77	436 CD	245 B
342	Mathura	UP	0.32	0.80	2.5	323	0.8	83	83	79	89	73	77	98	75	60	342 C	253 B
343	Bundi	RA	0.23	0.41	1.8	464	0.4	87	86	79	94	57	67	74	68	31	509 D	292 B
344	Trissur (Trichur)	KE	0.04	0.09	2.3	510	0.5	84	40	79	84	20	59	51	27	79	541 D	390 C
345	Srinagar	JK	0.02	0.03	1.8	412	0.4	96	83	80	82	60	65	72	74	1	494 D	86 A

(Continued)

Annex Table 1. Water productivity variations across districts in India (*Continued*).

ID	Districts[1]	State	Total and Irrigated area (Million ha), production (Million mt), CWU (km^3), NET and WP (kg/m^3) of grains															
			Total				Irrigation				Other data							
			Area	Production	Yield	CWU	WP	CWU - % of total CWU	NET - % of irri CWU	Area - % of total	Production - % of total	Grian area - % of GCA	Grian irri. area - % of GIA	NIA - % of NSA	GIA - % of GCA	GWIRA - % of GIA	CWU in irrigated grain area	CWU in rain-fed grain area
			M ha	M Mt	tonne/ha	mm	kg/m^3	%	%	%	%	%	%	%	%	%	mm	mm
346	Chhatrapur	MP	0.34	0.34	1.0	301	0.3	88	88	80	88	85	99	45	69	53	332 C	176 A
347	Gazipur	UP	0.37	0.75	2.0	392	0.5	86	56	81	91	91	93	81	79	78	416 C	286 B
348	Varanasi	UP	0.46	0.99	2.2	408	0.5	87	57	81	91	89	92	83	79	47	436 CD	288 B
349	Tirunelveli Kattabomman	TN	0.11	0.36	3.4	457	0.7	94	64	82	93	60	68	69	73	46	525 D	141 A
350	Aurangabad	BI	0.24	0.46	1.9	486	0.4	93	61	82	89	90	89	95	83	19	548 D	199 A
351	Hoshiarpur	PU	0.27	0.89	3.3	329	1.0	89	52	82	91	73	78	73	77	84	355 C	209 A
352	Lucknow	UP	0.17	0.32	1.9	377	0.5	87	64	82	91	74	74	87	82	79	399 C	276 B
353	Rae Bareli	UP	0.38	0.73	1.9	407	0.5	88	62	83	92	90	92	84	81	54	434 CD	279 B
354	Nawada	BI	0.15	0.28	1.8	412	0.4	89	45	83	89	97	94	84	85	44	441 CD	272 B
355	Gurdaspur	PU	0.44	1.69	3.8	367	1.0	93	55	83	92	86	86	72	84	91	410 C	154 A
356	Faridabad	HA	0.20	0.65	3.3	343	1.0	90	83	83	95	75	75	76	83	79	370 C	211 A
357	Nalanda	BI	0.24	0.48	2.0	404	0.5	90	51	84	90	95	98	85	82	68	432 CD	256 B
358	Haora	WB	0.12	0.27	2.2	479	0.5	85	29	85	88	69	93	46	63	9	482 D	462 C
359	Ambala	HA	0.20	0.65	3.2	397	0.8	91	52	85	95	84	85	81	84	87	426 CD	229 B
360	Mainpuri	UP	0.27	0.68	2.5	370	0.7	90	67	86	93	88	87	94	87	76	388 C	263 B
361	Moradabad	UP	0.52	1.35	2.6	375	0.7	90	65	86	94	64	66	82	84	98	391 C	277 B
362	Rohtak	HA	0.34	0.90	2.7	349	0.8	91	81	86	96	75	78	87	83	27	370 C	218 A
363	Rupnagar	PU	0.17	0.60	3.4	364	0.9	88	56	87	94	81	82	80	86	84	369 C	331 C
364	Pudukkottai	TN	0.10	0.31	3.1	601	0.5	96	69	87	95	62	86	63	63	22	662 D	188 A
365	Saharanpur	UP	0.20	0.50	2.6	354	0.7	95	62	87	94	45	46	91	85	82	385 C	147 A
366	Hisar	HA	0.55	1.94	3.5	320	1.1	95	92	87	96	57	54	87	93	19	348 C	130 A
367	Jehanabad	BI	0.15	0.28	1.9	443	0.4	92	46	87	92	90	89	100	89	51	468 CD	271 B
368	Hoshangabad	MP	0.49	0.80	1.6	401	0.4	93	92	89	93	56	93	73	53	29	423 C	234 B
369	Kanniyakumari	TN	0.03	0.14	4.1	502	0.8	97	59	89	96	34	70	35	42	6	548 D	143 A
370	Faizabad	UP	0.48	1.07	2.2	412	0.5	92	53	89	95	87	89	91	87	88	427 CD	294 B
371	Kodagu	KA	0.04	0.09	2.2	491	0.5	92	39	89	96	34	85	2	35	0	507 D	353 C
372	Chittoor	AP	0.10	0.23	2.2	609	0.4	97	76	89	97	21	44	42	43	66	658 D	198 A

(Continued)

Annex Table 1. Water productivity variations across districts in India (*Continued*).

ID	Districts[1]	State	Total and Irrigated area (Million ha), production (Million mt), CWU (km^3), NET and WP (kg/m^3) of grains															
			Total					Irrigation				Other data						
			Area	Production	Yield	CWU	WP	CWU - % of total CWU	NET - % of irri CWU	Area - % of total	Production - % of total	Grian area - % of GCA	Grian irri. area - % of GIA	NIA - % of NSA	GIA - % of GCA	GWIRA - % of GIA	CWU in irrigated grain area	CWU in rain-fed grain area
			M ha	M Mt	tonne/ha	mm	kg/m^3	%	%	%	%	%	%	%	%	%	mm	mm
373	Bareilly	UP	0.39	0.87	2.2	412	0.5	93	53	90	95	72	73	76	89	76	428 CD	278 B
374	Hardwar	UT	0.09	0.21	2.4	359	0.7	95	56	90	95	50	54	81	83	0	382 C	163 A
375	Bijnor	UP	0.18	0.51	2.8	371	0.8	91	63	91	96	39	43	82	81	98	373 C	345 C
376	Datia	MP	0.18	0.28	1.6	310	0.5	94	88	91	95	88	96	47	83	40	321 C	203 A
377	Shahjahanpur	UP	0.50	1.36	2.7	406	0.7	95	58	92	96	83	86	79	88	91	420 C	256 B
378	Chengaianna	TN	0.25	0.85	3.3	696	0.5	97	65	92	97	70	72	86	89	31	736 D	254 B
379	Rampur	UP	0.28	0.80	2.8	426	0.7	95	53	92	97	80	80	94	92	85	437 CD	282 B
380	Ernakulam	KE	0.04	0.07	1.8	529	0.3	95	37	92	94	17	39	29	40	27	545 D	326 C
381	Sirsa	HA	0.31	1.19	3.8	304	1.3	98	96	94	98	50	50	84	92	19	319 C	85 A
382	Pilibhit	UP	0.29	0.84	2.9	417	0.7	96	48	94	97	77	78	88	93	74	426 CD	276 B
383	Jind	HA	0.35	1.18	3.3	396	0.8	98	82	95	99	76	79	88	91	40	407 C	182 A
384	Yamunanagar	HA	0.13	0.42	3.3	415	0.8	97	53	96	99	66	71	88	90	98	418 C	348 C
385	Muzaffarnagar	UP	0.18	0.59	3.3	334	1.0	99	77	96	98	36	36	98	95	75	343 C	111 A
386	West Godavari	AP	0.47	1.55	3.3	604	0.5	98	52	96	99	70	79	83	86	52	616 D	288 B
387	Sonipat	HA	0.24	0.78	3.3	426	0.8	98	77	97	99	83	84	89	96	47	432 CD	236 B
388	Ghaziabad	UP	0.10	0.32	3.1	360	0.8	99	76	97	99	46	46	100	96	88	368 C	107 A
389	Meerut	UP	0.18	0.58	3.3	322	1.0	99	81	97	99	36	36	96	97	84	329 C	84 A
390	Kaithal	HA	0.33	1.19	3.6	415	0.9	99	75	98	99	91	90	99	100	45	419 C	211 A
391	Kapurthala	PU	0.23	0.95	4.1	405	1.0	99	71	98	99	85	84	96	100	99	409 C	156 A
392	Ludhiana	PU	0.53	2.34	4.4	420	1.1	99	71	99	99	86	85	96	100	98	423 C	228 B
393	Amritsar	PU	0.72	2.80	3.9	405	1.0	100	73	99	100	86	86	95	99	57	408 C	45 A
394	Bulandshahr	UP	0.45	1.39	3.1	363	0.9	99	67	99	100	68	70	84	97	85	364 C	285 B
395	Fairdkot	PU	0.80	3.34	4.2	403	1.0	100	88	99	100	72	72	93	99	93	406 C	63 A
396	Jalandhar	PU	0.47	1.88	4.0	394	1.0	100	67	99	100	78	80	91	97	97	396 C	134 A
397	Firozpur	PU	0.64	2.65	4.1	403	1.0	100	88	100	100	70	71	96	98	69	405 C	20 A
398	Sangrur	PU	0.78	3.41	4.4	439	1.0	100	82	100	100	87	87	96	100	69	440 CD	155 A
399	Patiala	PU	0.63	2.69	4.3	466	0.9	100	68	100	100	79	81	93	97	97	467 CD	259 B

(Continued)

Annex Table 1. Water productivity variations across districts in India (*Continued*).

			Total and Irrigated area (Million ha), production (Million mt), CWU (km^3), NET and WP (kg/m^3) of grains															
			Total					Irrigation				Other data						
ID	Districts[1]	State	Area	Production	Yield	CWU	WP	CWU - % of total CWU	NET - % of irri CWU	Area - % of total	Production - % of total	Grian area - % of GCA	Grian irri. area - % of GIA	NIA - % of NSA	GIA - % of GCA	GWIRA - % of GIA	CWU in irrigated grain area	CWU in rain-fed grain area
			M ha	M Mt	tonne/ha	mm	kg/m^3	%	%	%	%	%	%	%	%	%	mm	mm
400	Karnal	HA	0.34	1.27	3.7	461	0.8	100	70	100	100	89	91	100	98	66	462 CD	258 B
401	Panipat	HA	0.16	0.54	3.4	461	0.7	100	74	100	100	80	84	100	95	82	461 CD	245 B
402	Kurukshetra	HA	0.28	0.90	3.3	486	0.7	100	62	100	100	94	94	98	100	74	486 D	
403	Bathinda	PU	0.58	2.28	3.9	365	1.1	100	90	100	100	61	62	95	99	23	365C	
	Total or average (% grain irrigated area >25%)																	
	CWU < 225 mm	1	0	0	1	177	0.5	85	78	32	35	84	69	42	39	0	466	39
	225 mm < CWU < 300 mm	36	12	17	1.5	274	0.6	61	51	43	67	61	63	47	42	58	397	190
	225 mm < CWU < 475 mm	185	56	123	2.1	382	0.6	72	46	65	83	68	76	60	58	62	446	266
	475 mm < CWU	29	8	20	2.4	526	0.4	81	45	69	85	65	77	56	59	44	597	279
	Total or average	251	76	160	2.1	382	0.5	72	47	62	81	67	74	57	56	59	457	256

[1] Districts are sorted in terms of increasing percentage of irigated grain area

Analyzing the Impact of Quality and Reliability of Irrigation Water on Crop Water Productivity Using an Irrigation Quality Index

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Introduction

The past 30 years have seen major changes in the criteria for evaluating irrigation systems from the classical irrigation efficiencies to measuring performance using a variety of indicators (see Bastiaanssen and Bos 1999), such as taking into account productivity of irrigation water with the accent on yield (Perry and Narayanamurthy 1998; Sarwar and Perry 2002; Seckler et al. 2003); revenue enhancement per unit of depleted water (Barker et al. 2003); and equity in water distribution (Svendson and Small 1990). As scarcity of irrigation water is becoming evident in many regions and the demand for water increasing from other competing sectors of use (Perry and Narayanamurthy 1998; Amarasinghe et al. 2007), there is a need is to assess the quality of irrigation services in relation to productivity of water rather than in relation to productivity of land (Sarwar and Perry 2002). This means that the factors that need to be taken into account for assessing the quality of irrigation also need to change, the reason being the factors that influence yield are not exactly the same as those which influence water productivity.

The key drivers of change in water productivity are: 1) amount of water depleted in crop production, which changes both the numerator and denominator of productivity parameters; 2) all crop inputs including crop variety, fertilizer and pesticide dosage and labor, which determine the crop yields and net returns, change the numerator of water productivity. Now let us see how the reliability and quality of irrigation affects these drivers and thereby water productivity: It is an established fact that crop yield or biomass production increases in proportion to the increase in transpiration. However, at higher doses, irrigation does not result in beneficial transpiration, but in non-beneficial evaporation. In this way, increased evapotranspiration does not result in a proportional increase in the yield of crops (Vaux and Pruitt 1983). Non-recoverable deep percolation is another non-beneficial component of the total water depleted from the crop land during irrigation (Allen et al. 1998). This also increases at a higher dosage of irrigation.

With greater quality and reliability of irrigation, the farmers might be able to provide optimum dosage of irrigation to the crop, controlling the non-beneficial evaporation and non-recoverable deep percolation. This will result in the consumed fraction remaining low, while the fraction of beneficial evapotranspiration within the consumed fraction (CF) or the depleted water will remain high.[1] Also, it is possible that with a high reliability regime of the available supplies, even under scarcity of irrigation water, the farmers can adjust their sowing time such that they are able to provide critical watering, thereby obtaining high yield responses. Both result in higher water productivity. Furthermore, if more reliable irrigation water is available, farmers would be encouraged to use high yielding varieties, and apply an adequate amount of fertilizers and pesticides to their crops, resulting in better crop yields. Hence, the overall outcome of improved quality and reliability of irrigation would be higher water productivity.

In this paper, the following are attempted: i) developing quantitative criteria for measuring the quality and reliability of irrigation water at the farm level that will capture the complex physical variables relating to irrigation and affecting crop water productivity; ii) assessing the impact of quality and reliability of irrigation on water productivity in agriculture, through an analysis of individual crops; and iii) analyzing the factors that cause differential water productivity, which change due to change in quality and reliability regime.

Review of Literature on Analyzing the Performance of Irrigation Systems

Lately, irrigation researchers worldwide have begun to show a keener interest in trying to develop indicators for measuring the performance of irrigation systems and also to assess the impact of different irrigation management strategies on crop yields and productivity of land and water quantitatively, in view of the growing shortage of irrigation water, and the competing demands for water from other sectors. Four main strategies which were examined are: 1) providing deficit irrigation; 2) improving the timeliness of irrigation; 3) precision irrigation; and 4) improving the quality and reliability of irrigation. One of the motivating factors behind this is to identify the best strategy for improving the performance of irrigation systems, given its potential as a powerful tool to manage the demand for water in agriculture.

Svendson and Small (1990) analyzed the farmers' perspective of irrigation system performance. They found that the way farmers evaluate the performance of irrigation systems is by mainly focusing on the outcome and impact of the irrigation systems, and not so much by the process involved in managing irrigation such as staffing policies of the agency, pattern of communication and nature of farmers' participation in water users associations. According to Svendson and Small (1990), the ten important measures that farmers would use to assess irrigation system performance are: depth related measures viz., adequacy, equity and timeliness; farm management related measures such as tractability, convenience and predictability; and water quality related measures viz., temperature, sediment content, nutrient content; toxins and pathogens. But, how these criteria could be converted into normative indicators for analyzing irrigation system performance, or even strategies for improving the same were not addressed.

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[1] See Allen et al. (1998) for detailed discussion on various components of the applied water, such as consumed water, consumed fraction, beneficial transpiration, non-beneficial evaporation from the soil and non-recoverable deep percolation.

Bastiaanssen and Bos (1999) argued that a new generation of irrigation performance indicators such as adequacy, equity and productivity could be quantified using remote sensing data, based on previous work by several scholars such as Azzali and Menenti (1987), Bastiaanssen (1998), Menenti et al. (1989), Moran (1994), Roerink et al. (1997). For instance, Menenti et al. (1989) measured equity in irrigation water distribution by evaluating the actual flow per unit of irrigated area, at different spatial scales, in which the irrigated area was measured using satellite data. Moran (1994) used vegetation index and surface temperature to assess the adequacy. Bastiaanssen (1998) expressed adequacy in irrigation as a ratio of the total energy consumed by the crop in the form of ET and the total energy available for ET, and computed it from the surface energy balance. The study argued that equity in irrigation performance could be evaluated by taking a digital overlay of the Solar Energy Balance (SEB), with administrative boundaries and calculating the coefficient of variation across space. Roerink et al. (1997) extended the ET fraction approach used by Bastiaanssen (1998) and calculated the coefficient of variation of actual ET over total water supplied to quantify productivity.

Anecdotal and research based evidences of differential productivity gains in well irrigation over canal irrigation vis-à-vis yield and water productivity exist. This gain has been attributed to virtues of well irrigation over canal irrigation such as timeliness, greater quality in terms of adequateness and control over water delivery (Chakravorthy and Umetsu 2004; IRMA/UNICEF 2001; Kumar and Singh 2001). Some empirical studies showed the positive impact of the timeliness of irrigation on paddy yields in the canal command areas (Meinzen-Dick 1995). Other studies showed higher yield and net returns for crop production in diesel-engine irrigated crops over electric-pump irrigated ones (Kumar and Patel 1995), with the difference being attributed to better access to and control over irrigation, being possible with diesel-engine operated wells, i.e., the ability of the farmers to irrigate the crop as and when required, or better ‘timeliness’.

Studies in Pakistan Punjab showed that farmers who used conjunctive irrigation in canal command areas obtained greater yields than those who used only canal water for their wheat and rice crops (Hussain et al. 2003). A study by Sarwar and Perry (2002) in the Indus Plains of Pakistan, which simulated crop growth and ET under different irrigation schedules by using SWAP (Soil-Water-Atmosphere-Plant) model, showed that it is possible to enhance crop water productivity through deficit irrigation. The study showed 47 % higher crop water productivity under deficit irrigation conditions as opposed to unrestricted irrigation supply conditions, which led to the conclusion that while applying water to meet the exact crop water requirement would be the right strategy under situations of plentiful water, as regards in situations of scarcity, restricted water supply would be the strategy to maximize the productivity of water. Nevertheless, whether irrigation is in a deficit regime or in a water surplus regime is highly crop specific. And, as such, actual impacts on crop production cannot be assessed realistically, unless the farmers’ responses in terms of crop choices are also modeled.

According to another analysis by Perry and Narayanamurthy (1998), rationing irrigation to make it available during critical stages, which corresponds to crop growth stages where yield sensitivity to ET is high, is a useful strategy in enhancing crop yields. However, there are practical problems in assessing the quality of irrigation in terms of water availability during critical stages, and then applying it to devise an appropriate water delivery policy for an irrigation scheme. First, the farmers’ sowing time for crops varies significantly within the same irrigation command, and thereby changes the timing for critical waterings across the farms. Second, farmers in many irrigation systems in Asia grow multiple crops with the result that the critical stage with respect to 'growth response to ET' differs widely. Moreover, the quality of irrigation available from an irrigation system cannot be assessed in relation to water availability during the critical stage alone.

In a nutshell, the review of available irrigation literature shows that the studies cover either an analysis of different indicators for assessing irrigation system performance from different perspectives (farmers and irrigation agencies; use of different scientific methodologies to assess the performance of irrigation schemes in terms of crop yields or crop growth) or different approaches to improve the performance of irrigation systems in terms of their outcomes, under a set of conditions existing in the field vis-à-vis crops and climate. If not, there are mere qualitatively analysis of the impact of quality of irrigation on crop yields. But, it is important to note here that the real field outcomes of introducing irrigation management strategies suggested by such crop growth-based econometric models (see for instance, Perry and Narayanamurthy1998) would deviate far from the model predictions. This is due to the reason that such models fail to take into account the farmers' decision-making variables with regard to crop choices under different irrigation water supply regimes. Most of the studies assess productivity in relation to land.

Such studies, therefore, leave major information gaps about the governing parameters that can be manipulated for the performance improvement of irrigation systems, which are also crucial for working out their operational policies. There is hardly any empirical research that attempts to develop quantitative criteria, which use measurable physical indicators, for assessing the quality and reliability of irrigation and to capture complex variables such as the timeliness of irrigation, physical access to irrigation water source, water delivery rates and control over water delivery.[2] Such quantitative measures are important for working out operational policies for irrigation management.

Furthermore, very little is known about how improved quality and reliability of irrigation cause differential productivity, and the extent to which such factors contribute to water productivity changes. Instead, best known are the physical processes involved in plant growth, and the manner in which that changes with irrigation. But, what is needed is the real life impacts of different irrigation management interventions like improving 'quality and reliability' of irrigation on productivity of water.

The Study Objectives and Methodology

Study Location

In the Bist Doab area of Punjab, the climate varies from semi-arid to hot, sub-humid from south-west to north-east (Hira and Khera 2000). The Bist Doab area provides a unique opportunity to analyze the impact of the reliability of irrigation on crop yields and water productivity, the reason being the presence of farmers using canal water, groundwater and

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[2] This does not ignore the fact that several scholars had highlighted the need for improving the timeliness or irrigation on crop yields (Meinzen-Dick 1995); providing watering at critical stages of crop growth (Perry and Narayanamurthy 1998); and deficit irrigation under situations of water scarcity as crucial factors in enhancing productivity (Sarwar and Perry 2002).

both in the same location with a similar agro-climate. Also, incidentally, there are pockets where reliability of canal irrigation is quite high, against locations which are traditionally known for poor quality canal irrigation, overcoming the problem of wrongly attributing differential productivity to a particular source of irrigation.

One of the locations (Changarwan Village) chosen for the study in Hoshiarpur District receives an adequate amount of canal water from the Shah Neher Canal. Very few farmers have wells, and are located outside the command. But, farmers who receive canal water do not practice well irrigation. The area, which is part of the sub-mountainous region of Punjab, receives nearly 900 mm of rainfall, and is hot and sub-humid. The second location (Skohpur Village) located in Nawanshehr District is well known for intensive well irrigation, and the canal water supply is generally poor, except in very good rainfall years. The area receives a mean annual rainfall of approximately 450 mm (source: based on Hira and Khera 2000). Most of the farmers who receive canal water also practice well irrigation, at least for some crops.

Objectives

The overall objective of this paper is to analyze the impact of quality and reliability of irrigation water on the water productivity of crops. This is done by comparing the physical productivity of water and water productivity in economic terms for individual crops, under different types of irrigation systems with differential quality and reliability.

The specific objectives are to: 1) Develop a composite index for quality and reliability of irrigation water, that is relevant for three different types of irrigation systems, viz., canal irrigation, well irrigation and conjunctive method of irrigation, at the field scale; 2) Estimate the values of the index for the irrigation water supply condition in two locations in Bist Doab area; 3) Analyze the impact of quality and reliability of irrigation water on crop water productivity and cropping pattern in the Doab area; and 4) Analyze the factors responsible for differential productivity of water use in crop production.

Methodology, Data and Sampling

The quality and reliability of irrigation would influence water productivity in many different ways. First, good quality and reliable irrigation services would provide farmers with the opportunity of optimizing the dosage of irrigation, which can help prevent the non-beneficial evaporation of soil moisture from the field during the crop development stages and residual moisture in the soil after the crop harvest, thereby bringing the depleted water close to beneficial ET. Reliable and quality irrigation would motivate farmers to use fertilizers adequately, use high yielding seed varieties, invest in agronomic practices and also go for high-valued crops that involve more risk. This would positively affect the yield. Since, differential input costs need to be factored in the productivity analysis, the combined physical and economic productivity of water also needs to be compared. Furthermore, since the cropping pattern might change from one source to another, overall net water productivity (Rs/m^3), including all the crops, needs to be compared for understanding the real impact of improved quality and reliability of irrigation.

Since there are perceptible differences in the quality and reliability of irrigation between canal irrigation and well irrigation, and also between well irrigation and conjunctive use, the impact of reliability and quality on water productivity can be compared by comparing the field level water productivity of applied water for the same crop for these different sources (both in

Kg/m^3 of applied water and Rs/m^3 of applied water). But, it is also important to quantify the quality and reliability of irrigation using certain realistic criteria based on physically measurable indicators. Then the productivity values for different sources can be compared against the estimated values of quality and reliability of the source.

In order to analyze the factors responsible for differential water productivity, or identify the determinant of water productivity that changes with quality and reliability of irrigation, the data on crop inputs viz., labor use, fertilizer and pesticide use were analyzed for all the farms and the mean figures were compared.

The sample size for Changarwan Village is 36, 18 each of farmers using canal irrigation and well irrigation supply. In case of Skohpur Village the sample size is 35, of which 21 farmers use well irrigation and 14 farmers have adopted the conjunctive use method. Among these, there are three farmers who for certain crops use only canal water supply for irrigation.

Primary data were collected from the sample farmers, in both locations using real time monitoring. The data collected included: area under different irrigated crops; date of sowing and harvesting; the actual irrigation schedules, including the timing and duration of each watering; crop outputs; the price of produce (price at which it is being procured by the Food Corporation of India); the discharge of pumps; and the canal discharge rate.

Analytical Procedure

The differential quality and reliability of irrigation vis-à-vis a crop can be quantitatively estimated by using certain irrigation related physical parameters. They are: water control index; number of irrigations; average duration per watering per unit cropped area; and maximum time duration between two waterings during the entire crop season.

It is argued here that higher frequency improves the quality and reliability of irrigation. The reason is that a greater frequency of irrigation reduces the chances of moisture stress. Also, the greater the duration of watering, the better would be the quality. Greater duration of water delivery would enhance the chances of improving field application efficiency. On the contrary, greater the time gap between two farmers watering for the same crop, the poorer would be the quality of irrigation and greater would be the chances for crop damage due to water stress. The correct dosage of water, by maintaining the delivery rate, could prevent the leaching of fertilizers and other nutrients in the soil, thereby maintaining good growth.

Quality and reliability of irrigation for wells, canals and conjunctive use for a farmer l, with respect to a given crop is assessed in terms of an irrigation quality index (δ_l) defined by

$$\delta_l = \frac{In_{\ l}\ Id_{\ l}\psi_{\ l}}{t_{\ l}} \quad \text{...} \quad 1$$

$$\psi_{\ l} = [\ aq - bq_l^2\ ] \text{ where, } a = 0.13 \text{ and } b = 0.0026$$

Where ψ_l is the water control index for farmer l, ln_i and ld_i are the number of times of irrigation and duration of irrigation (hr/ha), respectively, given by the sample farmer l for a crop; t_l is the maximum time duration between any two consecutive waterings given by sample farmer l for the crop in days. q_l is the rate of water delivery (l/s) for that farmer. It is assumed that a water delivery rate of 15 liters per second is best for the crop for which the index would be one and accordingly the values of coefficients a and b were estimated.[3]

From the index δ obtained for each farmer in the sample, the mean values would be estimated and compared against the field level water productivity.

The detailed analytical procedure employed for estimating water productivity parameters is available in Kumar et al. (2008).

The computed value of irrigation quality index can be interpreted as higher the value of the index, higher is the quality and reliability of irrigation water delivered to a given field.

Results and Discussion

Irrigation Quality Index for Different Irrigation Systems

Based on real time data on irrigation schedules, duration of irrigation and the water delivery from the source, the irrigation quality (IQ) index was estimated for all the sources, viz., well irrigation, conjunctive irrigation and canal irrigation. The estimates for Changarwan are provided in Table 1 and that for Skohpur are provided in Table 2. As Table 1 shows, the IQ value is higher for well irrigation for all crops except paddy. This is understandable. In the case of wells, for a given crop, the number of irrigations was much higher. Also, the time gap between two consecutive watering was lower. In the case of paddy, the value of the index is slightly higher for canal irrigation.

Table 1. Estimates of irrigation quality index for canal irrigation and well irrigation at Changarwan (Zone 1) for selected crops.

Name of Season	Name of Crop	Source of Irrigation	Irrigation Quality Index (IQ)
Kharif	Paddy	Well	2.66
		Canal	3.33
	Maize	Well	10.28
		Canal	0.65
	Bajra	Well	1.37
		Canal	0.25
Winter	Wheat	Well	2.26
		Canal	0.5
	Barseem	Well	0.44
		Canal	0.17

Source: Authors' own analysis based on primary data

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[3] The relationship between q and ψ was assumed to be convex, defined by a quadratic equation. The highest value of the water delivery index was assumed to be 'one' at the delivery rate of 15 liters per second. At that level, the slope, i.e., differential d ψ_I/d q will be zero.

In the case of Skohpur, there are three sources of irrigation, i.e., well, canal and conjunctive use. The computed values of IQ are higher for well irrigation except for kharif bajra and maize. For maize, the IQ value is highest for conjunctive irrigation, and in the case of bajra the value is highest for canal irrigation.

Table 2. Estimates of quality and reliability for well irrigation, canal irrigation and conjunctive use at Skohpur (Zone 2) on selected crops.

Name of Season	Name of Crop	Source of Irrigation	Irrigation Quality Index (IQ)
Kharif	Paddy	Well	26.77
		Canal	13.51
		Conjunctive	28.16
	Maize	Well	2.63
		Canal	2.2
		Conjunctive	5.01
	Bajra	Well	1.44
		Canal	2.29
		Conjunctive	1.16
Winter	Wheat	Well	1.05
		Canal	0.87
		Conjunctive	1.25
	Barseem	Well	1.43
		Canal	1.17
		Conjunctive	0.32

Source: Authors' own estimates based on primary data

Water Productivity of Different Crops

The mean value of crop yields, and estimated mean value of irrigation dosage, and water productivity in physical and economic terms for the major crops viz., paddy, maize, bajra, wheat and barseem for well irrigated crops and canal irrigated crops are presented separately in Tables 3 and 4. Comparing crop yields between irrigation sources show higher yield values for canal irrigated fields. The comparison shows the following: 1) the irrigation dosages are much higher for canal-irrigated fields for all five crops mentioned above; 2) physical productivity of water is higher for well-irrigated fields, for paddy, maize and wheat; and 3) the values of water productivity in economic terms are higher for well- irrigated fields for maize, bajra and wheat.

The irrigation dosages are excessive for fields which are receiving canal water. Even so, the yields are much higher for these fields when compared to well-irrigated fields in spite of the fact, that the well irrigated fields are getting adequate quantities of water. One important reason for these differences in yield viz., canal irrigation is the chemical quality of the canal water. As reported by the farmers in Changarwan Village, the canal water that comes from the

Bhakra irrigation scheme in Punjab-Himachal border is very rich in many minerals present in its hilly catchments in the Shivalik hills. The continuous availability of this water for the past four decades had made the land receiving this water also very fertile. Hence, the nutrient regime in the soil is much higher in the canal irrigated fields.

Table 3. Water productivity estimates of different crops under well irrigation at Changarwan (Zone 1).

Well Irrigation					
Name of Crop	Total Irrigation Water Applied [m^3/acre]	Crop Yield [kg/acre]	Net Income [Rs/Acre]	Water Productivity in Main Product [kg/m^3]	Water Productivity [Rs./m^3]
Paddy	3,518.5	1,169.5	548.8	0.57	0.32
Maize	598.7	941.7	1,629.3	1.53	6.44
Bajra	1,497.9	6,025.0	3,425.5	7.82	0.43
Wheat	915.4	1,003.6	754.1	1.97	4.45
Barseem	1,184.5	4,864.6	9,474.0	1.72	12.99

Source: Authors' own estimates based on primary data

Table 4. Water productivity estimates of different crops under canal irrigation at Changarwan (Zone 1).

Canal Irrigation					
Name of Crop	Total Irrigation Water Applied [m^3/Acre]	Crop Yield [kg/Acre]	Net Income [Rs/Acre]	Water WaterProductivity in Main Product [kg/m^3]	Productivity [Rs/m^3]
Paddy	5,849.8	1,661.2	6,183.8	0.41	1.50
Maize	2,600.0	880.0	4,336.2	0.53	2.00
Bajra	1,935.8	8,122.2	7,358.2	10.41	0.09
Wheat	1,109.0	1,100.6	2,465.4	1.57	3.46
Barseem	2,488.5	7,216.7	16,454.0	3.60	24.01

Source: Authors' own estimates based on primary data

The mean value of crop yields, estimated irrigation dosage, and estimated water productivity in physical and economic terms for the major crops irrigated by wells, canals and conjunctive method in the Skohpur Village are presented separately in Tables 5, 6 and 7, respectively. Comparison across sources shows the following: 1) the depth of irrigation is highest for fields irrigated by canals, followed by conjunctive use, and lowest for wells i.e., for paddy and wheat; 2) the yield is higher for well irrigated fields for paddy and barseem, whereas it is higher for canal irrigated fields in the case of maize; 3) the physical productivity of water is higher for well irrigated fields in the case of paddy, bajra and wheat, and highest for canal irrigated fields in the case of maize. As regards water productivity in economic terms, values were higher for well-irrigated fields for all crops except bajra.

Table 5. Water productivity of different crops under well irrigation at Skohpur (Zone 3).

Well Irrigation					
Name of Crop	Total Irrigation Water Use [m³/Acre]	Crop Production [kg/Acre]	Net Income [Rs/Acre]	Water Productivity in Main Product [kg/m³]	Water Productivity [Rs/m³]
Paddy	4,548.0	2,270.0	12,520.7	0.79	4.46
Maize	1,381.0	1,060.0	310.3	3.30	6.34
Bajra	1,040.9	5,607.8	-244.40	17.21	0.37
Wheat	697.5	1,494.1	8,584.8	3.41	19.80
Barseem	3,050.6	6,214.3	12,676.8	3.52	30.28

Source: Authors' own estimates based on primary data

Table 6. Water productivity estimates of different crops under canal irrigation at Skohpur Village (Zone 3).

Canal Irrigation					
Name of Crop	Total Irrigation WaterApplied [m³/Acre]	Crop Production [kg/Acre]	Net Income [Rs/Acre]	Water Productivity in Main Product [kg/m³]	Water Productivity [Rs/m³]
Paddy	11,722.6	1,766.7	3,966.2	0.20	0.06
Maize	2,836.1	1,260.0	6,656.4	9.15	1.99
Bajra	6,433.6	4,500.0	1,752.2	1.45	1.03
Wheat	1,787.0	1,592.9	9,820.0	2.37	14.32
Barseem	2,382.3	5,400.0	11,263.7	2.41	10.56

Source: Authors' own estimates based on primary data

Table 7. Water productivity estimates of different crops under conjunctive use of irrigation at Skohpur Village (Zone 3).

Conjunctive Use					
Name of Crop	Total Irrigation WaterApplied [m³/Acre]	Crop Production [kg/Acre]	Net Income [Rs/Acre]	Water Productivity in Main Product [kg/m³]	Water Productivity [Rs/m³]
Paddy	7,740.0	2,188.9	11,628.3	0.79	4.19
Maize	1,247.4	783.3	1,635.8	0.73	1.50
Bajra	475.20	8,600.0	4,400.0	9.05	4.38
Wheat	1,745.0	1,518.3	9,528.8	2.51	16.99
Barseem	3,909.6	5,675.0	8,869.40	3.76	9.73

Source: Authors' own estimates based on primary data

Relationship between Quality and Reliability of Irrigation and Water Productivity of Crops

Table 8 shows the estimates of irrigation quality index (IQ) for five major crops under two major sources of irrigation, viz., wells and canals, and the corresponding estimates of physical and economic productivity of water for these crops for Changarwan Village. It can be seen that in situations where the irrigation quality index is higher, the water productivity in economic terms is higher as well. The only exception is barseem. Another interesting observation is that water productivity in economic terms does not follow the same trend as that of physical productivity of water. The physical productivity of water was found to be higher for fields, which have lower irrigation quality index, e.g., paddy, bajra and barseem.

One reason for this could be the difference in duration of the crop between fields under different sources of irrigation. In crops such as bajra and barseem where only leafy biomass is harvested, if water is available in plenty through excessive water delivery, farmers might take more harvests of these fodder crops with a greater number of irrigations. This would reduce the value of IQ, but may not reduce the physical productivity of water as the biomass output would increase in proportion to the amount of water used.

Table 8. Productivity of water for crops at Changarwan (Zone 1).

Name of Crop	Source of Irrigation	Irrigation Quality Index (IQ)	Water Productivity (kg/m^3)	Water Productivity (Rs/m^3)
Paddy	Well	2.66	0.57	0.32
	Canal	3.33	0.41	1.50
Maize	Well	10.28	1.53	6.44
	Canal	0.65	0.53	2.00
Bajra	Well	1.37	7.82	0.43
	Canal	0.25	10.41	0.09
Wheat	Well	2.26	1.97	4.45
	Canal	0.5	1.57	3.46
Barseem	Well	0.44	6.53	12.99
	Canal	0.17	10.23	24.01

Source: Authors' own estimates based on primary data

Table 9 shows the estimates of irrigation quality index for five major crops under well irrigation, canal irrigation and conjunctive use, and the corresponding estimates of physical productivity and economic productivity of water for these crops for Skohpur Village. Similar to what was seen in the case of Changarwan, comparing well irrigated crops and canal irrigated crops in Skohpur shows that water productivity (Rs/m^3) was found to be higher for fields, which have higher irrigation quality and reliability, except for paddy.

Table 9. Productivity of water for crops at Skohpur (Zone 3).

Name of Crop	Source of Irrigation	Irrigation Quality Index (IQ)	Water Productivity (kg/m^3)	Water Productivity (Rs/m^3)
Paddy	Well	26.77	0.79	4.46
	Canal	13.51	0.20	0.06
	Conjunctive	28.16	0.79	4.19
Maize	Well	2.63	3.30	6.34
	Canal	2.2	9.15	1.99
	Conjunctive	5.01	0.73	1.50
Bajra	Well	1.44	17.21	0.37
	Canal	2.29	1.45	1.03
	Conjunctive	1.16	9.05	4.38
Wheat	Well	1.05	3.41	19.80
	Canal	0.87	2.37	14.32
	Conjunctive	1.25	2.51	16.99
Barseem	Well	1.43	3.33	30.28
	Canal	1.17	2.41	10.56
	Conjunctive	0.32	2.02	9.73

Source: Authors' own estimates based on primary data

Impact of Quality and Reliability of Irrigation Water on Drivers of Change in Crop Water Productivity

We have begun our analysis with the premise that improved quality and reliability of irrigation, expressed in terms of irrigation quality index (IQ), would be able to manipulate the water productivity parameters through controlling the major drivers of change in water productivity such as irrigation dosage, fertilizer and pesticide inputs.

Increase in irrigation dosage, to a great extent, increases the beneficial evapo-transpiration from the crop and, therefore, the crop yield. But, excessive irrigation will not have any positive effect on crop yields. On the other hand, it increases the denominator value of water productivity. We have seen that the IQ values are much higher for well-irrigated fields of both locations. Similarly, for most crops in Changarwan, the irrigation dosages are much lower for well-irrigated fields than for canal-irrigated fields. The trend was the same in the case of Skohpur. The irrigation dosage was much higher in the canal irrigated fields and in the fields irrigated by both canals and wells, than that of well-irrigated fields for most crops samples of Sokhpur Village.

This means that the highest influence of IQ is in controlling the water delivery in the field. A lower IQ meant a higher dosage of irrigation and vice versa. Actually, lower number of irrigations and shorter durations of watering, which have a negative effect on the dosage of irrigation, reduce the value of IQ. But, the only factor which actually increases the dosage of irrigation is the excessively high discharge rate, which reduces the value of the water control index. For instance, in the case of canal irrigated fields in Skohpur, the discharge rates measured were in the range of 54 m^3/hour to 136.8 m^3/hour, whereas the discharge rate varied from 35.46 to 67.9 m^3/hour for wells (source: field level measurements).

Excessive dosage of irrigation is likely to reduce both the physical and economic productivity of water. But, fertilizer and pesticide dosage and labor input are also other drivers of change in water productivity as they can increase the yield, without changing the denominator of water productivity in kg/m^3. Generally, their effect on the physical productivity of water would be positive. At the same time, these inputs can increase the cost of production significantly and, therefore, its marginal impact on the net returns may not be always positive. We have begun our analysis with the assumption that better quality and reliability in irrigation services would lead to optimal use of other inputs such as fertilizers, pesticides and labor.

Comparative analysis of crop inputs such as fertilizer, pesticide and labor use between crops which receive irrigation of differential quality and reliability does not fully support this hypothesis. In Changarwan, for instance, the change in levels of fertilizer and pesticide dosage with the change in source of irrigation was found to be significant only for paddy, wheat and maize. What emerges from the comparison is that the dosage of these inputs does not increase with the increase in irrigation quality index (Table 10). The canal-irrigated fields, which get less reliable supplies, do not necessarily receive a lower dosage of fertilizer and other inputs. One reason for this could be that as the irrigation dosage is very high in the case of canal-irrigated fields resulting in heavy percolation, farmers provide for leaching of fertilizers, which occur due to it. Another reason could be that quality and reliability does not matter so much for fodder crops such as bajra and barseem, and that farmers try to obtain higher yield through a higher dosage of inputs.

Table 10. Comparison of input use and water productivity in economic terms at Changarwan Village (Zone 1).

Name of Crop	Source of Irrigation	Irrigation Quality Index (IQ)	Input Use (Rs/Acre)		Water Labor (Rs/Acre)	Productivity (Rs/m^3)
			Fertilizer	Pesticide		
Paddy	Well	2.66	607.8	179.0	1,393.81	0.32
	Canal	3.33	701.5	157.0	1,207.37	1.50
Maize	Well	10.28	566.3	135.5	333.3	6.44
	Canal	0.65	272.3	196.2	666.6	2.00
Bajra	Well	1.37	215.0	-	1,200	0.43
	Canal	0.25	242.9	-	-	0.09
Wheat	Well	2.26	629.1	176.0	918.6	4.45
	Canal	0.5	775.5	169.8	944.6	3.46
Barseem	Well	0.44	438.5	120.0	560	12.99
	Canal	0.17	426.5	350.0	300	24.01

Source: Authors' own estimates based on primary data

A significant difference in labor use was found between sources for three crops viz., paddy, maize and barseem. Here, contrary to what was generally perceived, labor input was higher for fields which received irrigation water of lower reliability.

Analysis for Skohpur (Table 11) shows that there is no general pattern in the input use vis-à-vis source of irrigation or quality and reliability of irrigation. Similarly, in the case of labor input also, no general pattern is seen to be emerging. As a result, lower quality and reliability of irrigation does not necessarily result in lower water productivity in physical terms but in economic terms, as shown by a majority of the cases from both the field locations.

Table 11. Comparison of input use and water productivity in economic terms at Skohpur Village (Zone 3).

Name of Crop	Irrigation Quality Index (IQ)	Source of Irrigation	Input Use (Rs/Acre)		Labor (Rs./Acre)	Water Productivity (Rs./m^3)
			Fertilizer	Pesticide		
Paddy	26.77	Well	1,004.9	151.9	1,032.0	4.46
	13.51	Canal	857.70	245.7	1,195.2	0.06
	28.16	Conjunctive	1,019.4	196.0	1,047.6	4.19
Maize	2.63	Well	954.0	228.4	1,201.2	6.34
	2.2	Canal	1,058.7	148.9	966.6	1.99
	5.01	Conjunctive	1,007.3	178.3	281.5	1.50
Bajra	1.44	Well	345.0	-	845.0	0.37
	2.29	Canal	500.0	55.0	500.0	1.03
	1.16	Conjunctive	-	-	-	4.38
Wheat	1.05	Well	835.2	199.2	824.8	19.80
	0.87	Canal	1,080.7	206.7	727.7	14.32
	1.25	Conjunctive	875.9	165.6	1,300.0	16.99
Barseem	1.43	Well	535.9	-	-	30.28
	1.17	Canal	591.0	495.0	466.6	10.56
	0.32	Conjunctive	675.0	175.0	-	9.73

Source: Authors' own estimates based on primary data

Impact of Differential Quality and Reliability of Irrigation Water on the Cropping Pattern

The quality and reliability of irrigation had some impact on the cropping pattern chosen by the farmers. The area allocated by well irrigators for maize during kharif was higher in Changarwan as compared to canal irrigators (see Tables 12 and 13). Obviously, maize consumes far less water when compared to paddy; however, it is not a highly water-efficient crop. There are two reasons for the greater preference for maize. One is the water shortage during summer

Table 12. Comparison of cropping pattern at Changarwan Village (Zone 1).

Name of Crop	Percentage area under source	
	Well	Canal
Paddy	31.41	43.41
Maize	11.42	2.37
Bajra(GF)	5.21	7.14
Wheat	44.85	42.15
Barseem	5.93	4.90

Source: Authors' own estimates based on primary data

Table 13. Comparison of cropping pattern at Skohpur Village (Zone 3).

Name of Crop	Percentage area under source		
	Well	Canal	Well + Canal
Paddy	24.1	9.99	48.90
Maize	18.5	25.8	7.52
Bajra (GF)	4.56	8.43	1.25
Wheat	42.3	44.5	28.5
Barseem	6.72	10.2	4.7

Source: Authors' own estimates based on primary data

months induced by a restricted power supply in the farms[4] and the other is the high cost of diesel required for pumping groundwater. This makes paddy production with diesel-pump irrigation an unattractive proposition for the farmers. But, the canal irrigators in the same village (Changarwan) get plenty of canal water for paddy, with good reliability as seen from the estimates of quality and reliability of canal water supply for paddy in that village. Hence, they are able to allocate more land for paddy.

In the Skohpur Village the reliability of canal water supply is very poor. This is indicated by the figures of irrigation quality and reliability index estimated for canal water supplies for paddy, which have been subsequently confirmed during discussions with farmers. The lower reliability of canal water supplies is forcing farmers to allocate a smaller area for water-intensive paddy. The main reason for this is that the returns from paddy are dependent on the adequacy of irrigation water applied, as seen from the comparison of net returns from paddy. While the well irrigators get net returns of Rs.12,000 from an acre of paddy, the canal irrigators get only Rs.3,900 per acre in that village. Hence, we could infer that quality and reliability of water influences the cropping pattern wherein the farmers choose crops that give a higher return from every unit of land they cultivate, if quality and reliability of irrigation water is good.

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[4] In Punjab, monsoon arrives in the first week of July, while the transplanting of paddy starts in June itself. During the month of June, the potential evapotranspiration of the crop rapidly goes up due to very high temperatures and high aridity, and the crop needs frequent waterings (Hira and Khera 2000).

Conclusions

In our research, we have developed quantitative criteria for assessing the quality and reliability of irrigation water at the field scale, and using these criteria, a composite index called the irrigation quality index was developed. The index uses the water control index, a function of water delivery rate; the frequency of irrigations; the duration of irrigation; and the maximum time gap between two consecutive waterings as the determinants. The values of the index are computed with reference to a crop, and hence the values obtained for two different crops are not comparable. The values of the index were worked out at the field level under three different sources of irrigation in the Bist Doab area.

The estimates of irrigation quality index were found to be higher for well irrigated fields as compared to canal irrigated fields and fields irrigated by both wells and canals in Skohpur Village. But, the same were found to be higher for canal irrigated fields in the case of the Changarwan Village for paddy. This is in confirmation with what the farmers in these villages perceive about the quality and reliability of irrigation water deliveries from canals from the respective villages. Hence, we could conclude that the quantitative criteria evolved for estimation of this composite index are realistic.

Comparison of the values of irrigation quality index estimated for major crops under different sources of irrigation vis-à-vis the water productivity of the respective crops show that differential reliability has an impact on economic productivity of water (Rs/m^3). The fields, which received irrigation water of higher quality and reliability, got higher water productivity in Rupee terms. But, the impact of differential quality and reliability was not manifest in the physical productivity of water for fodder crops.

The findings of our research contradict the conventional wisdom that higher quality and reliability of irrigation would result in better yields at least for one location, i.e., Changarwan. But, the deviation found in this case could be due to the differences in the chemical quality of water, which the index could not capture. Nevertheless, one can conclude that improved quality and reliability of irrigation would help enhance the water productivity in crop production. The research also showed that quality and reliability of irrigation water also had a significant impact on the cropping pattern. Nevertheless, the index developed here is not adequate to assess the IQ of crops, which can be harvested many times during the crop season. Also, the irrigation quality index needs refinement so that it could account for differences in the chemical quality of irrigation water.

Policy Inferences

The research gives sufficient indications to irrigation water policymakers in India on the need to invest in improving the quality and reliability of water supplies from the schemes, be it public irrigation systems like canals or private irrigation systems like wells. It also shows that the parameters that need to be manipulated to improve the quality and reliability of irrigation water are frequency of irrigation, duration for which water is available to the field, and discharge rate. The frequency of irrigation has to increase; the time gap between two waterings has to reduce; the duration for which water is available to the field has to increase; and the discharge has to be moderate, not too low and not too high.

In the case of public canals, achieving this would call for major changes in the paradigm of the irrigation scheme design itself. For instance, reducing the discharge rate for the water courses would mean reducing the size of the chak[5] itself, which is normally of 40 ha. In order to increase the frequency of water delivery, it is important that the minors run at the full supply level throughout the season. The success of it again would depend on whether the scheme has got adequate amount of water or not. But, in the short and medium term, what is achievable is the creation of intermediate storage systems below the delivery outlets (minor outlets) so as to enable the farmers to use the water as and when needed in a controlled way. By doing this, three important parameters governing quality and reliability of irrigation, viz., frequency of watering, duration of water supply and water delivery rate could be manipulated at the field scale. Nevertheless, in the irrigation command having wells, quality and reliability of irrigation can be enhanced remarkably by providing supplementary irrigation through these wells, when the canal water is not available.

In the case of well-irrigated areas, providing good quality power supply is the key to farmers securing good control over water delivery to their crops, thereby securing higher returns per unit of land and water. The comparative analysis of water productivity in diesel-pump irrigated farms and electric-pump irrigated farms, where in the case of the former, there is a higher return per unit of land and water (Singh and Kumar 2008; Kumar et al. 2008), are testimony to this.

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[5] A 'chak' refers to the area commanded by a minor, which is the canal off-taking from a distributory of an irrigation system.

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Water Productivity of Different Agricultural Systems

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Introduction

Agriculture is the major consumer of water among various sectors. Growing demands of water for urban areas and environmental management are projected to reduce the diversion of water for agriculture in the future. On an average annual basis more water will be required to feed the growing and wealthier populations with their more diversified diets (CA 2007). Climate change is also projected to have implications for water and agriculture and, as such, must be considered to determine the way water is being managed now and in the future as well. Enhancing water productivity in agriculture is an appropriate response to counter the increasing levels of water stress. Given the growing water scarcity that is resulting from increased water demand, the challenge is to increase water productivity for food and livelihoods and, thereby usher in an era of the 'evergreen revolution'. It can help alleviate poverty through improved access to water for the poor and also have multiplier effects on food security, employment and livelihood. Besides the physical availability of water, yet another cause for concern in obtaining the maximum agricultural output, or value for every drop of water used in agriculture, is the economical accessibility of water.

High water productivity may not be a suitable target, where the concurrent opportunity costs or forgone values, like the alternative potentials of the saved or lost water, are not taken into account (Zoebl 2006). Understanding the concept of agricultural water productivity and exploring opportunities for its enhancement in irrigated, rain-fed and waterlogged areas through integrated and multiple uses assume greater importance. It is very important in groundwater irrigated areas, where water is either scarce due to faster depletion of aquifers, as in the western Indo-Gangetic (IG) basin, or it is costlier to pump water, as in the eastern part of the IG basin owing to the use of diesel operated pumps. Rain-fed agriculture, occupying 60 % of the net sown area of the country, may be a more economic target for enhancing water productivity.

Most of the water productivity studies deal with crop water productivity with a single crop, or single water use with the exception of limited studies on water productivity in dairy production. Agriculture with improved water management system and/or integrated farming and multiple water use systems i.e., using the available water source(s) for more than one production system (crops, horticulture, livestock, fisheries etc.,) is one of the responses to produce 'more food with less water'. The paper presents agricultural water productivity for farming systems based on multiple water use, and crop water productivity under different water management systems.

Water Productivity

Water productivity is used exclusively to denote the amount or value of product over volume or value of water used or depleted or diverted (Kijne et al. 2003). Water productivity will depend on many factors other than the quantity of water applied or depleted. Though water is only one of the factors of agricultural production and cannot be meaningfully separated from the others, an estimate of its productivity and knowledge about the factors which influence the productivity will help understand the pathway to improving water productivity.

Agricultural water productivity takes into account multiple water users, including conventional crops, horticulture, forestry, livestock, fisheries, environment etc. It means that if all water users are taken into account and a concept of recycling and reuse of water is considered in an agricultural production system, then agricultural output per unit of total water input is referred to as agricultural water productivity. Since agricultural water productivity assessment considers the multiple uses of water, its value represents a composite or an integrated picture that is higher than the crop water productivity.

Water productivity analysis can be applied to crops, livestock, tree plantation, fisheries, and mixed systems at selected scales-crop or animal, field or farm, irrigation system, and basin or landscape, with interacting ecosystems. Since expressions for water productivity differ in each context, it is important to be clear about the agricultural output and input terms used. As regards agricultural systems, agricultural water productivity will be the sum total of factor productivity from crops, livestock, fishery, horticulture etc. However, care will have to be exercised to avoid multiple accounting of the same input.

Livestock water productivity is a measure of the ratio of outputs, such as meat, milk, eggs or traction, to water depleted, and is defined as a scale-dependent ratio of livestock production (or services) produced per unit of water depleted (Peden 2003). Methodology must be integrated with other crop, forestry and fisheries uses of water resources in the watershed/basin in order to harness the full advantage of multiple uses in an integrated farming systems approach. Livestock produced solely with irrigated forage and grain crops will have far lower water productivity when compared with livestock production relying on the consumption of crop residues, grazing and tree fodder, as the water used for plants would have been used with or without livestock feeding on it and feed is a by-product of crops (Singh and Kumar, this book). The fishery, as such, is considered nonconsumptive in terms of water use. But, when water is diverted and stored in ponds for fish, some water will be depleted through evaporation from the pond. Where fish production occurs by virtue of irrigation and/or water harvesting reservoirs, its benefit is added to water without additional depletion, and so it enhances water productivity for the same quantity of water depleted. If we increase production by keeping water in the reservoir for summer months when there are no standing crops, there would be additional evaporation which needs to be accounted for. Chapagain and Hoekstre (2003) have also cautioned against avoiding double and under accounting of water used for livestock products.

Assessment of Agricultural Water Productivity

Agricultural water productivity may be computed for the crop period or for the whole year considering the production value—first from crops only (crop water productivity) and then considering other water users including trees, livestock and fish in case of multiple uses per unit of water inflow (including rainfall, groundwater and canal water) as well as water used (total inflow excluding runoff) in the field, farm, irrigation system, basin and landscape. The values of denominator i.e., water input may be different for different situations. In the estimation of water productivity, we are interested in water inflows (rain plus irrigation, or just rainwater in rain-fed agriculture) and water depletion (evaporation and transpiration). The amount of water depleted through evapotranspiration by crops will not be considered again while accounting for depletion in case of crop residues/ straw for livestock, to avoid double accounting. Similarly, in case of fisheries, water depletion through storage losses is to be considered as input only when water storage in the pond/ tank is exclusively maintained for breeding fish.

Case Studies of Agricultural Water Productivity Assessment

Canal and Tubewell Commands

Assessment of water productivity in mixed use systems including crops, livestock, fisheries, and trees in the irrigation command of RP Channel-V of Patna Main Canal in the Sone Command at Patna and in the tubewell command area in Vaishali, Bihar is discussed. Crop water productivity was computed considering crop output per unit of irrigation water applied, inflow diverted (including rainfall, groundwater and canal water) as well as water used (total inflow excluding runoff), whereas agricultural water productivity was computed considering the output of various water uses like cereal crops, horticulture, trees, fisheries and livestock. Water productivity was computed during kharif (monsoon) and rabi (winter) seasons considering the production value— first from crops alone and then considering other water uses including trees, livestock and fish (Sikka et al. 2008).

1. Survey and Data Collection/Measurement

A comprehensive survey was undertaken in the RP Channel V command and tubewell command area at Vaishali, and data/information from 90 farmers of the former and 85 farmers of the latter, were collected during kharif (monsoon) and rabi (winter) season. The comprehensive survey included: number of family members, number of farm workers, total area, total area in the command, details of trees, livestock, inputs (seed, fertilizer, manures, pesticides, weedicide, irrigation water and human labor), total input cost and total output (main product and by product).

2. Estimation of Value Production

Value of Crop Production: Data regarding the various aspects of cultivation of different crops such as area under each crop, quantity and value of various inputs used, quantity and value of the main product as well as by-products produced were collected from farmers in the selected commands. From this data average value production per hectare was worked out for various crops grown in the commands in kharif as well as in rabi seasons. This average value product includes both the main product as well as the by-product. Actual area under different crops was derived from the plot-wise data obtained from GIS mapping technique. Value production of each crop was derived by multiplying the area under each crop with the respective average value of the product per unit area. The value product from various crops was added to get the total value of production from crops.

Value from Trees: Data regarding the number and type of trees grown, quantity and value of the main product as well as by-products obtained from the trees was collected from the farmers. As trees are perennial, it was difficult to collect such data for a particular season and data was instead, collected for one year. From this data the average value production per tree per year was worked out separately for various species. The actual number of trees belonging to different species were counted and recorded. The average value of production was multiplied with the number of trees of different species and added together to get the value of production from trees per year in the command. While estimating the value of the product, biomass addition in the trees was not included. Similarly, the wood value of trees was also not considered. Only the value of fruits, firewood and fodder was considered.

Value from Fish: Fish production was very limited in the selected commands. Only three farmers were engaged in fish production in outlet 4 of the RP Channel V. Data regarding the production aspects of fish were collected and value from fish production was estimated accordingly.

Value from Livestock: Average quantity of milk and dung produced per animal per day was worked out from the data collected from the farmers. This was multiplied with the actual number of animals in the command area to get the total production per day. Average prices were used to value this physical production. Total value from livestock per day was obtained by multiplying physical production. Then this value was multiplied by the number of days in the accounting period to get the total value of production per command. But this entire value of production cannot be attributed to the command area, as the livestock are not dependent on the production from the command area alone. Feed and fodder come from the outside also. Command is meeting only 23–40 % of the fodder requirement. As the total fodder cost in milk production was about 60 %, only 60 % of the value product was attributed to fodder. Since 23–40 % is met from the command area, that percentage of the value of production was attributed to the command area. No additional water input is considered for feed and fodder, which is met from the command area, as the total water applied from the outlet to the command is already accounted for, and feed and fodder are by products of the main crops.

The following assumptions were made while valuing the production from livestock in the study:

- The fodder cost in the total cost of milk production was assumed to be 60 %. Hence 60 % of the production was considered from fodder
- Services from bullocks were not considered
- Animals not in lactation period were not considered while calculating milk production
- Increase in body weight of the animal and calves produced were not included
- Value of grass grown on bunds and grass grazed by animals could not be considered

3. *Estimation of Total Water Inflow*

- All the different sources of water to the command of RP Channel-V of Patna Main Canal in the Sone Command at Patna and tubewell command in Vaishali were identified. The command area of RP Channel-V is irrigated by canal and tubewell, while the command area of the Vaishali District is mostly irrigated by tubewell.
- To carry out the measurements of the volume of water reached to the fields, three outlets—at head, middle and tail reaches were selected in RP Channel-V to install V-notch. Flow data from three outlets, at the head, middle and tail reaches were collected with the help of V-notch for both kharif and rabi seasons. Whereas for the tubewell command area at Vaishali, data were collected for pumping hours also with the help of V-notch.
- Water head at the outlet of RPC-V was measured on a daily basis and the total water delivered was also calculated on a daily basis. For calculating discharge in the channel, the volume of water flowing at the head, middle and tail is calculated with help of V-notch.
- Daily precipitation was recorded using rain gauge.

The total water entering the domain (rainfall, canal and tubewell) was calculated for the respective command area and the same was incorporated in the SWAP model. Water diverted to the command areas of RP Channel–V and tubewell commands in Vaishali was found to be utilized by different crops. SWAP model was used to calculate interception, runoff, evaporation and transpiration separately. The water balance components for both kharif and rabi crops were calculated for all three outlet commands and two tubewell commands. The details are available in Sikka et al. (2008).

Finally, water productivity was computed considering value from crop production, trees, fish and livestock and water diverted by various users, as given in Table 1.

Table 1. Crop and agricultural water productivity.

Water Productivity (Rs/m^3)	Outlet 4 Head Reach	Outlet 17 Middle Reach	Outlet 27 Tail Reach	Tubewell 2 Land consolidation	Tubewell 11- Fragmented landholding
Area (ha)	30.61	43.68	4.65	18.74	13.21
Crop WP per unit of irrigation water applied	4.79	4.95	8.39	29.61	14.03
Crop WP per unit of water inflow including rainfall	2.42	2.73	3.11	2.81	2.39
Agricultural WP per unit of irrigation water applied	5.28	5.90	10.66	38.73	18.09
Agricultural WP per unit of water inflow including rainfall	2.67	3.25	3.96	3.68	3.09

Source: Sikka et al. (2008)

Crop water productivity (Rs/m^3) in relation to applied water ranged from 4.79 to 8.39. When rainfall was also included in the inflow, it ranged from 2.42 to 3.11 in the outlet commands. In tubewell commands, the applied water productivity ranged from 14.03 to 29.61, whereas it was in the range of 2.39 to 2.81 when rainfall was also included. Agricultural water productivity (Rs/m3) considering applied water varied from 5.28 to 10.66. When rainfall was also considered, it was between 2.67 and 3.96 in the outlet commands. In tubewell commands, the agricultural water productivity ranged from 18.09 to 38.73 for applied water and 3.09 to 3.68 for total water inflow including rainfall. Lower water productivity under total inflow in tubewell command may be attributed to very high proportion of rainfall in the total water used. The analysis indicates that both in the canal commands and tubewell commands, agricultural water productivity of applied as well as total water inflow (including rainfall) taking into account other water users like trees, fodder, livestock, fish etc., provides a better picture of the actual productivity of water.

Water Productivity in Multiple Use Systems

Integrated farming systems and the multiple uses of water provide great opportunities for enhancing the water productivity of agriculture and livelihood at various scales by integrating fisheries, livestock, aquatic crops, horticulture etc., with crops into the existing irrigation and water use systems/water infrastructures. Evidences of such multiple use systems (MUS) could be found in canal and groundwater irrigated, rain-fed, waterlogged, coastal and hilly areas/watersheds. Besides increasing water productivity, MUS system also reduces the investment costs and risks associated with single use. Analysis of factor and total water productivity of the sub-system and system as a whole also provides an insight into the tradeoffs for alternative options. Some examples of agriculture water productivity of multiple use systems are discussed below.

Secondary Reservoir-cum-Fish Pond in Tubewell Irrigation

Routing of tubewell water for irrigation through a secondary reservoir-cum-fish pond to enhance water productivity is another example. In a study at ICARRCER, Patna routing of tubewell water from secondary reservoir gave additional benefits in terms of a fish harvest of 11.0 t/ha with weekly water exchange during summer (Bhatnagar et al. 2004). The factor of water productivity in breeding fish in the secondary reservoir was computed after accounting for depletion through evaporation from the reservoir during the off-crop period and the amount of water exchanges required after maturity of the rabi (winter) crop. The factor of water productivity for the fishery was estimated to be Rs 16.11/m^3, with an evaporation of 137.44 m3 and an additional water exchange of 406.25 m3 (Bhatnagar et al. [Draft Bulletin]). Water productivity of the system could easily be further increased by making beneficial use of the exchanged water for raising vegetables.

Multiple Use Systems (MUS) in Waterlogged Areas

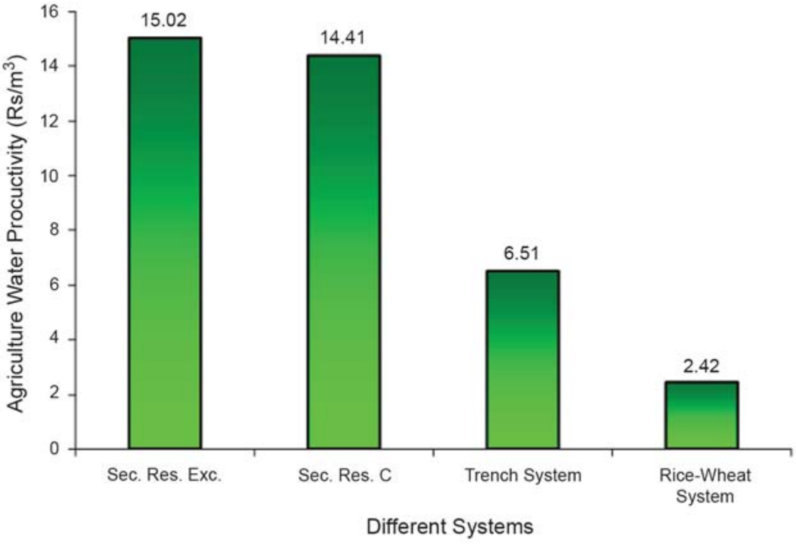
(i) To enhance productivity of seasonally waterlogged lands in canal commands, secondary reservoir (fed by canal seepage and supplemented by tubewell), fish trenches-cum-raised bed for fish-horticulture production and rice-fish culture using nylon-pen under waterlogged area, were undertaken at ICARRCER, Patna. In the secondary reservoir concept, two reservoirs were constructed in the seasonal waterlogged area. Multiple uses of water by fish culture in reservoir, horticulture (two tiers: banana/ guava/ lemon and vegetables) on bunds, routing water to cereal crops, and duck-rearing were evaluated. Water was supplemented from tubewell to maintain a minimum water level in the reservoir for fish production (Sikka et al. 2008).

Agricultural water productivity for the three types of farming systems based on multiple water use was analyzed taking into account the water diverted into the pond to replenish water in the seepage fed pond during the lean season and valuation of outputs from crops, vegetables fruits, eggs, and fishes for the year. Water productivity values for different MUS systems are shown in Figure 1. The results indicate about 2.7 to 6 fold increase in water productivity by integrating different components over the traditional rice-wheat system. Water productivity was maximum (Rs.15.02/ m3) in the secondary reservoir (with exchange of water) where fish, fruits, vegetables and duck-rearing were integrated with rice and wheat, as against Rs.2.42/ m3 in the rice-wheat system alone.

The economic analysis indicates that integrating fish in the rice-wheat system gave a net income of Rs. 29,694/ha, which is 6 % higher than the traditional rice-wheat system yielding of Rs. 27,965/ha per year. Under seasonally waterlogged areas up to 1m depth, a system based on fish trenches-cum-raised beds horticulture and fish system generated a net income of Rs.80,951/ha/year, which is 189 % higher over traditional rice-wheat system. Under seepage-fed secondary reservoir supplemented with groundwater, a system of horticulture on bunds + fish + duckery yielded net returns of Rs.1,32,590/ha/year, which is 374 % higher over traditional rice-wheat system (Sikka et al. 2008).

(ii) Multiple water use based farming system with on–dyke horticulture and fish-prawn-poultry system in farmers' field in Orissa provided an excellent opportunity to productively use water- logged area. The farmers converted 2.47 ha of waterlogged area into 1.64 ha of pond and 0.83 ha of raised embankment. While the pond area was utilized for fish and prawn culture,

Figure 1. Agriculture water productivity of multiple water use systems at ICAR-RCER, Patna.



21 m wide embankment was used for planting mango, teak, areca nut, coconut, banana, papaya, pineapple, mushroom etc. Net water productivity of multiple use system was estimated to be Rs.7.5/m^3 against Rs.0.95/m^3 for lowland rain-fed paddy alone and Rs.6.0/ m^3 with vegetable production (Samra et al. 2003).

(iii) Aquaculture was integrated with the subsurface water harvesting structures (SSWHS) meant for providing irrigation during post monsoon season in the coastal areas of Orissa. Water productivity varied from Rs.15.84/m^3 to Rs.50.84/m^3 with an average of Rs.36.20/m^3 while taking the total income into account. Net water productivity (considering only benefits) ranged from Rs.9.00/m^3 to Rs.53.70/m^3 with an average of Rs.23.26/m^3 (Sahoo et al. 2003; Srivastava and Satpathy 2004).

Multiple Use Systems in Rain-fed Areas

The harvested water in the rain-fed areas can be judiciously used for multiple uses such as drinking, supplemental irrigation, livestock, fisheries etc., to optimize water productivity. Integrated farming system based on multiple uses of water in low to high rainfall rain-fed regions while improving productivity of water has provided additional monetary benefits to small and marginal farmers.

(i) Rainwater harvesting and multiple use-experience of Horticulture and Agro-forestry Research Program (HARP) of ICAR-RCER: In the experimental farm of HARP in Ranchi, a rainwater harvesting pond was constructed with a capacity of 1,200 m^3. The command area of 0.7 ha consists of litchi based multi-tier horticultural system. Fish production in the pond, vegetable/ fruits/ pulse production on the bunds (measuring 3.0 m width around the ponds), supplemental irrigation to cereal production on a limited area of 0.125 ha with surplus runoff storage during monsoon season, and irrigation through gravity fed drip irrigation to multi-tier horticulture are the multiple uses of the harvested rainwater in the system. The farming system accounts for the production of cereals, pulses, oilseed, fruits, vegetables and fish and thus offers income diversification for the marginal tribal farmers and a regular flow of income. Agricultural water productivity (with total water depletion of 826 m^3) was estimated to be Rs.31/m^3 for the farming system as a whole during the year 2007 (Personal Communication 2009).

(ii) Multiple uses of harvested rainwater in undulating terrains of the eastern plateau has been demonstrated by constructing an unlined tank of 1,468 m^3 with a catchment and command area of 3 ha and 0.95 ha, respectively (Srivastava et al. 2004). Fish and prawn was grown in a pond with two rows of papaya planted on the embankment and one row of banana planted on the free board area of the inward slope. Water productivity (on the basis of utilized water) increased from Rs.3.84/ m^3 for crop alone to Rs.5.35/m^3 with multiple water use (Srivastava and Satpathy 2004).

Water Productivity (WP) of Different Water Management Systems

There are many well known crop water productivity improvement measures including supplemental and deficit irrigation, water saving devices, soil conservation, soil fertility improvement and resource conservation technologies (RCTs) like zero-tillage and bed planting. However, assessment of WP improvements under such situations is lacking. An attempt is made to present some values in this regard.

WP under RCTs

A study was carried out in Pabnawa Minor of Bhakra Canal System in Kurukshetra, Haryana to assess water productivity under zero-tillage and bed planting in rice-wheat system in the western IG plains (Chandra et al. 2007). In each of the four selected watercourses (Table 2), 15 farmers' fields were selected for detailed monitoring of water use and crop yields. In the selected fields in PH, PM1 and PT section of the water course, wheat was planted using zero-tillage and bed planting techniques. However, wheat crop was planted using conventional tillage practices in the selected fields of PM2 command. Information related with different agricultural and water management practices adopted by farmers in the selected fields, was collected on a specially designed data collection form. Systematic observations were recorded for water use on a daily basis from the selected farmers' fields.

Table 2. Details of selected watercourses.

Irrigation Minor	Watercourse	Technology	Design discharge (m^3/sec)	Gross command area (ha)	Cultivated command area (ha)
Pabnawa	Pabnawa Head-end (PH) 2820R*	Zero-tillage Bed Planting	0.028	231.6	208.9
Pabnawa	Pabnawa Middle (PM1) 53705L	Zero-tillage Bed Planting	0.041	320.2	300.0
Pabnawa	Pabnawa Middle (PM2) 53705 R	Conventional Tillage	0.025	341.3	169.6
Pabnawa	Pabnawa Tail-end (PT) 80000L	Zero-tillage Bed Planting	0.052	283.0	253.4

Source: Chandra et al 2007

Note: Letters L and R refer to left and right banks of the watercourse

Wheat water productivity in the bed planting method of crop establishment is generally higher than that under zero-tillage and conventional tillage (CT) at the plot level in the different reaches. Water productivity of wheat in bed planting (BP) is greater than that under zero-tillage and wheat water productivity in zero-tillage is greater than that under conventional tillage across plot to watercourse scales. The irrigation water productivity for rice under BP is higher (22 to 28 %) than that of CT, but land productivity is lesser than conventional tillage (Table 3). There is a trade-off between water productivity and land productivity in bed planted rice.

Results of this analysis indicate the superiority of zero-tillage over conventional tillage both in terms of the water productivity in irrigation and land productivity in wheat, besides profitability of wheat production. Water productivity under both zero-tillage and conventional tillage decreases as one moves from plot level to watercourse level (i.e., for the three levels of analysis). Higher level of water productivity under zero-tillage over conventional tillage at the

Table 3. Water and land productivity of bed planted rice and conventional tillage rice.

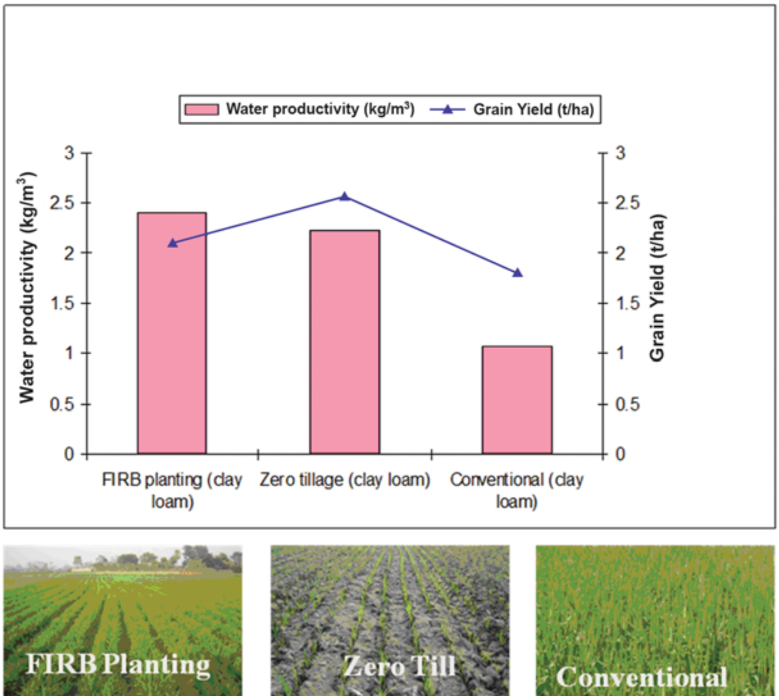
Location	Method of Sowing	Irrigation Water Productivity (kg/m^3)	Gross Water Productivity (kg/m^3)	Average Yield (t/ha)
PH	BP	0.38	0.37	4.76
PM1	BP	0.39	0.38	5.43
PT	BP	0.49	0.46	4.93
PM2	CT	0.31	0.30	5.53

Source:Chandra et al 2007

farm and watercourse level suggests benefits of water saving under zero-tillage at the watercourse level. These results are based on limited but rarely available field data. However, they do illustrate suggestive indicators of enhanced WP under RCTs.

Water productivity of wheat in the clay loam soils of Bihar in bed planting, zero-tillage and conventional tillage on the farmers' fields are shown in Figure 2. It is evident that water productivity is highest under bed planting followed by zero-tillage, with the lowest under conventional tillage. Though, the water productivity of wheat is slightly less in zero-tillage than in bed planting, land productivity is higher in zero-tillage over bed planting and conventional tillage. This suggests that there is a tradeoff between water and land productivity in bed planted wheat, and under a water-scarce situation bed planting may be preferred.

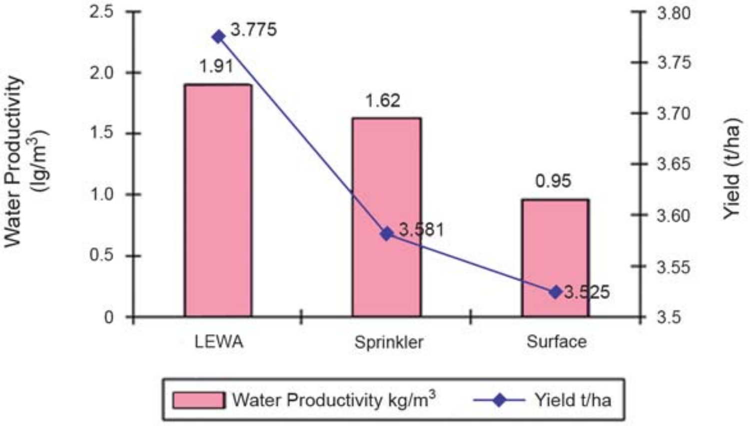
Figure 2. Water productivity and grain yield of wheat under different sowing methods.



WP under Micro-irrigation

Water productivity in Banana was raised by 72 % in a dry-land watershed at Saliyur in Coimbatore District when the conventional surface method of irrigation was replaced by drip irrigation. Water saving irrigation methods help in improving water productivity. Molden et al. (2007) have reported gains in water productivity varying from about 40 % to over 200 % for various crops (banana, sugarcane, cabbage, cotton, grapes, potato and tomato) in shifting from conventional surface methods to drip irrigation in India. Water productivity of LEWA (Low Energy Water Application) device for wheat at Patna was estimated to be 1.91kg/m^3 against 1.62 kg/m^3 and 0.95 kg/m^3 for sprinkler and surface methods of irrigation, respectively (Figure 3).

Figure 3. Water productivity and yield of LEWA in wheat.



Conclusions

The concept of agricultural water productivity and the methodologies for its assessment have been demonstrated through a number of field studies focused on multiple use based farming systems in the irrigated, rain-fed and waterlogged areas. Since agricultural water productivity takes account of different water uses and production systems, it presents a better and composite picture of water productivity obtained in farming systems. The advantages of harnessing synergies of multiple water use based farming systems are reflected in significantly higher values of agricultural water productivity as compared to crop water productivity alone. These results are based on simple but conceptualized methodology based on certain assumptions, which may have limitations in accounting procedures, and leave room for more elaborate field studies for evolving a comprehensive methodology of computing total and factor productivity of water in multiple water use based farming systems. The values of water productivity are based on the prevailing market prices of outputs for the respective years in different studies and, therefore, this limits their comparison on a relative basis for the given set of systems.

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Impact of Dairy Farming on Agricultural Water Productivity and Irrigation Water Use

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Introduction

India is the largest producer of milk in the world. The country's milk production had gone up from 22.51 million tonnes in 1970-71 to 80.81 million tonnes during 2000-01 with per capita milk availability increasing from 115.3 gm/day to 238.06 gm/day during the aforesaid period. Both semi-arid and arid regions and subhumid and humid regions have contributed to this growth (Singh and Pundir 2003). This achievement was possible with the gradual replacement of traditional breeds of livestock by high yielding ones (Pandey 1995). One of the most remarkable impacts of India's economic growth is on the demand for dairy products, unlike what has been found elsewhere in that the demand for meat products increase with growing income levels. In India, consumption of milk increased by 20 % in per capita terms during 1990-2005 (von Braun 2007). According to a recent projection, the consumption of milk products in India, which currently stands at nearly 185 gm/person/day, is likely to grow at a rate of 0.7 % per annum to reach 236 gm/person/day during 2000-2025 (Amarasinghe et al. 2007), further increasing the demand for increased production.

But, the likely impact of this trend on the country's land and water resources has not been analyzed. A recent research in North Gujarat, which is known for intensive dairy farming, has shown that dairying is the most water-inefficient production system, taking a lion's share of the precious groundwater resources in the region (Singh 2004; Kumar 2007). This has made many scholars argue that dairying in semi-arid regions could lead to an increased use of water in agriculture with direct impact on groundwater resources in such regions. But, the distinction between commercial dairy farming, which is intensive, and the one which complements crop production, and their implications for water intensity in dairy production, is hardly ever made.

The actual impact of dairy farming on water resources would depend on where all the milk is produced, and the nature of dairy farming. In this article, we provide comparative analysis of water productivity in crops and dairying in the two semi-arid regions, viz., North Gujarat and Punjab, and demonstrate how the opportunity for reducing groundwater depletion through enhancing water productivity of crops differs between the two regions, if socioeconomic concerns have to be integrated in regional water allocation decisions. The first region selected for the purpose is semi-arid North Gujarat, where farmers had taken up intensive dairy farming on a commercial basis, where intensively irrigated fodder crops like water-intensive alfalfa is fed to animals along with by-products of cereal crops like wheat, bajra and sorghum. The other region is south-western Punjab where cereals form a major portion of the irrigated field crops, and dairying is taken up as a supplementary activity in which by-products of crops are fed to animals.

The Context

In water-scarce regions, particularly in arid and semi-arid regions, heavy withdrawal of groundwater for irrigation is having several undesirable consequences. Demand management in agriculture is a standard approach to water management suggested for such regions (Kumar 2007). One important element of this approach works on water productivity of individual crops (as cited in Kumar 2007). Water productivity in agriculture refers to the biomass output or net income returns per unit volume of water applied or consumed for crop production.[1] It suggests replacement of cereal crops, which are economically less efficient in water use, with cash crops, which are economically more efficient in water use.

Semi-arid North Gujarat is one region in India where heavy withdrawal of groundwater for agriculture is causing secular decline in groundwater levels and scarcity of water for irrigation and drinking. Enormous increase in the cost of groundwater abstraction and increasing inequity in access to water are some of the socioeconomic consequences there. Throughout most of semi-arid Punjab, heavy withdrawal of groundwater is causing depletion, with negative economic and environmental consequences. With the demand for milk and dairy products growing in India, milk production is also increasing in many areas. More importantly, dairying is emerging as a major livelihood option in rural areas of semi-arid and arid regions facing water stress like North Gujarat, Kolar District in Karnataka and Alwar District in Rajasthan. One reason for farmers' preference for dairying as a livelihood option is the ability to manage the inputs such as feed and fodder through imports during scarcity.

Research conducted in North Gujarat had shown that dairying is highly water intensive, with estimated values of net water productivity in economic terms remaining far less than that of several conventional field crops. In case of cash crops, castor offered the highest net water productivity (Rs.7.21/m^3) and cotton the lowest (Rs.0.68/m^3). In case of food grains, highest net water productivity was found for kharif bajra and lowest for wheat crop with Rs.4.82 and 1.08 per m^3, respectively. In case of milk production, net water productivity for buffalo milk was Rs.0.19 per m^3 of water, whereas the net water productivity for crossbred cow was Rs.0.17 per m^3 (see Figure 1 based on Kumar 2007). Against this, in Punjab, the rice-wheat system of production is supposed to deplete its groundwater resources.

The natural course for agronomists and water resource managers to save irrigation water in regions such as North Gujarat is to replace dairy crops by some of the highly water-efficient fruit crops and vegetables. Whereas in Punjab, the suggestion often made by water resource scientists and water managers is to reduce the area under cultivation of paddy and wheat that take a lot of water in the form of evapotranspiration. Another suggestion was to delay the transplanting of paddy saplings during kharif to make use of the rains (Hira and Khera 2000).

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[1] While the first one is called physical productivity, the second one is called water productivity in economic terms.

But this approach has serious limitations in most situations. First, it ignores the linkages between different components within the farming system, which are often integrated. For instance, reduced cultivation of low water-efficient cereals and fodder could affect dry fodder availability, which could directly have an impact on dairying, a major source of income for millions of farmers. There is a need to recognize the fact that farmers allocate their water over the entire farm and not to individual crops. Unless we know about the comparative water productivity in dairying, decisions on changing crop compositions that help reduce water stress cannot be made. As a result, the unit of analysis of water productivity should be the farming system rather than the field. Second, it ignores the effect of such changes on local food security and livelihoods. For example, large-scale replacements of low, water-efficient cereal crop by a highly water -efficient cash crops by farmers in a region, might result in reduction of water use, but, it can also cause local food insecurity, and affect domestic nutritional security of farm households.

What Determines Water Intensity of Milk Production?

The water intensity of milk production is inversely related to its water productivity. Low water productivity means high water intensity. Water productivity in milk production is analyzed using the concept of 'embedded water', i.e., the amount of water depleted by the crops that are used as animal feed and fodder through evapotranspiration. The reason for this is that direct water consumption by cattle is low, whereas growing fodder and feed cereals need large quantities of water. The functional relationship between water productivity in milk production, and cattle inputs and outputs can be expressed as:

$$\sigma_{dairy,\,j} = \frac{Q_{MP}}{\Delta_{milk}} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (1)$$

Where $Q_{MP\,j}$ is the average daily milk yield of a livestock over the entire life cycle. Δ_{milk} is the total volume of water, including the water embedded in feed and fodder inputs, used by an animal in a day. Both are worked out for the entire animal life cycle. Δ_{milk} is estimated as:

$$\Delta_{milk} = \frac{Q_{cf}}{\sigma_{cf}} + \frac{Q_{df}}{\sigma_{df}} + \frac{Q_{gf}}{\sigma_{gf}} + \Delta_{drink} \quad \dots\dots\dots\dots\dots\dots \quad (2)$$

Where, Q_{cf} , Q_{df} and Q_{gf} are the average weights of cattle feed, dry fodder and green fodder used for feeding a livestock; σ_{cf}, σ_{df} and σ_{gf} are water productivity values (kg/m^3) of cattle feed, dry fodder and green fodder, respectively; Δ_{drink} is the daily drinking water consumption by livestock.

If water productivity of green fodder like fodder jowar, fodder bajra, and maize is high, then quantum of water used for dairying (Δ_{milk}) would be low. This can raise milk water productivity. If, on the other hand, the milk yield of the animal is high (Q_{MP}), then again, water productivity of milk production would be high. Similarly, if the amount of feed and fodder which an animal requires to be productive is low, then again milk water productivity will be high. Again, the feeding pattern would determine the amount of water needed. Wheat hay and paddy straw have high water productivity in kg/m^3. So, when farmers depend merely on these crop residues for feeding animals, water productivity will be high. But, intensive dairying would force farmers to grow fodder crops for this purpose, as crop residues won't be enough. Alfalfa, used as green fodder, is highly water-intensive.

The water productivity in crop production can be estimated in relation to the total water consumed by a crop during its growth (evapotranspiration), or the total irrigation water applied for crop production or the total effective water applied, which includes the irrigation dosage and effective rainfall. Since we are concerned with the depletion of water resources available from the groundwater system or surface flows for crop and milk production, it would be appropriate to consider the productivity of applied (irrigation) water. But, as the precipitation also contributes to the yield of many crops grown during the monsoon, it is important to estimate the marginal yield due to irrigation by segregating the rainfall contribution of the yield from the total yield. This has to be used in the denominator for estimating irrigation water productivity. However, for semi-arid and arid areas, the yield contribution of soil moisture from precipitation can be treated as negligible for most crops grown during the monsoon.[2] This would make marginal productivity of irrigation water equal to total productivity of irrigation water (Equation 3).

$$\text{Irrigation water productivity in crop production} \quad \sigma_{crop}\,(\text{kg/m}^3) = \frac{Y_{crop}}{\Delta_{crop}} \quad \text{............} \quad (3)$$

Nevertheless, such assumptions would induce significant errors in estimation of water productivity for kharif crops that are grown in humid and subhumid conditions. Hence, for such areas, the marginal productivity of irrigation water is estimated by running regression between yield and irrigation water dosage. The beta coefficient of regression equation gives the marginal productivity of irrigation water.

The estimated values of physical water productivity for crops and by-products are imputed in Equation (2) mentioned above to arrive at the value of Δ_{milk}. For by-products of crops that are used for dairy production as inputs, the total irrigation of water applied and cost of production of the crop are allocated between main product and by-products in proportion to the revenue generated from them, as suggested by Dhondyal (1987).

Water productivity in milk production in economic terms (θ_{diary}) is estimated by taking the ratio of net return from milk production (NR_{diary}) and the total volume of embedded water, and direct water use in milk production (Δ_{dairy}). Here again, the net returns are average values, estimated for the entire animal life cycle, taking into consideration the average milk yield worked out for the entire animal life cycle, the market price of milk and the cost of production of milk worked out for the animal life cycle.

$$\theta_{dairy} = \frac{NR_{diary}}{\Delta_{diary}} \quad \text{..} \quad (4)$$

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[2] Needless to say, for winter and summer crops, such assumption would be quite reasonable and would not result in errors in estimation as residual soil moisture for growing crops would be negligible.

Average Physical Productivity of Water in Milk Production in Two Semi-arid Regions

The physical productivity of water in milk production was estimated for two types of livestock in North Gujarat and three types of livestock in western Punjab. The input data used for this were average daily milk yield, the average daily quantities of dry and green fodder and cattle feed for the livestock (kg), the daily drinking water use by the livestock (m^3), all estimated for the entire animal life cycle and the physical productivity of water for different types of green and dry fodder (kg/m^3) estimated using the standard formula (for details see Kumar (2007) or Singh (2004)). Subsequently, the water productivity in milk production in economic terms was estimated using the average net return from milk production using the gross return and average production cost of milk.

The results are presented in Table 1. It shows that the physical productivity of water for both buffalo and cross bred cow is much higher in western Punjab, when compared to North Gujarat. Furthermore, the difference in economic productivity is much higher than that in physical productivity. In the case of western Punjab; the high physical productivity of water in milk production could be attributed to the lower volume of embedded water in the inputs used for cattle owing to higher physical productivity of both green and dry fodder. In the case of western Punjab, it was found that only green fodder, such as winter *jowar* (fodder) and kharif *bajra* (fodder), and dry fodder available from residues of paddy (hay) and wheat (straw), were used. Since paddy and wheat have very high yields in the region, the physical productivity of dry fodder is very high. The cumulative effect of both these factors is the lower amount of embedded water. Whereas in the case of North Gujarat, alfalfa, a highly water-intensive irrigated green fodder, was found to be most common.

Table 1. Milk yield and physical and economic productivity of water in milk production in two semi-arid regions.

Variables	Punjab			North Gujarat		
	Buffalo	Crossbred Cow	Indigenous Cow	Buffalo	Crossbred Cow	Indigenous Cow
Average Milk Yield (liter/day)	3.25	4.46	2.98	3.12	5.33	N. A
Water Productivity (WP) (liter/m^3)	1.79	2.53	3.68	0.31	0.49	N.A
WP in Milk Production (Rs/m^3)	7.06	17.44	16.41	0.190	0.17	N. A

Source: Based on Singh (2004) and Kumar et al. (forthcoming)

Note: N.A. denotes not applicable

The difference in feeding pattern can be seen from Table 2 below. Though the amount of green and dry fodder quantities are less in the case of North Gujarat, alfalfa (figures in brackets) accounts for nearly 70 % of the green fodder for both buffalo and cross-bred cow. Furthermore, the quantum of cattle feed used for dairy animals in North Gujarat is much higher

Table 2. Comparison of daily average feed and fodder consumption per milch animal in western Punjab and North Gujarat.

Feed/Fodder	Animal Type	Bathinda (Western Punjab)	Mehsana (North Gujarat)
Green Fodder (Kg/day)	Buffalo	19.46	12.98 (9.25)
	Indigenous Cow	12.92	Nil
	Crossbred Cow	14.41	12.96 (9.07)
Dry Fodder (Kg/day)	Buffalo	7.94	5.48
	Indigenous Cow	5.07	Nil
	Crossbred Cow	4.33	6.44
Concentrate (Kg/day)	Buffalo	2.28	5.21
	Indigenous Cow	1.2	Nil
	Crossbred Cow	1.4	5.36
Drinking Water (Liters/day)	Buffalo	55.8	59.10
	Indigenous Cow	52.6	Nil
	Crossbred Cow	60.2	49.10

Source: Kumar et al. (forthcoming) and Singh (2004)

than that that of western Punjab. The much higher water productivity in economic terms was due to: i) lower cost of production of milk, owing to the lower cost of production of cattle inputs such as dry and green fodder, resulting in much higher net returns; and, ii] the lower volume of embedded water in cattle feed and fodder. The difference in cost of inputs is mainly seen in irrigation water. In North Gujarat, pumping depths are much higher than that of Punjab. This results in very high capital and variable cost of irrigation owing to expensive deep tubewells, high capacity pump sets, and very high electricity charges.

Trade Offs between Enhancing Field-level Water Productivity and Regional Water Productivity

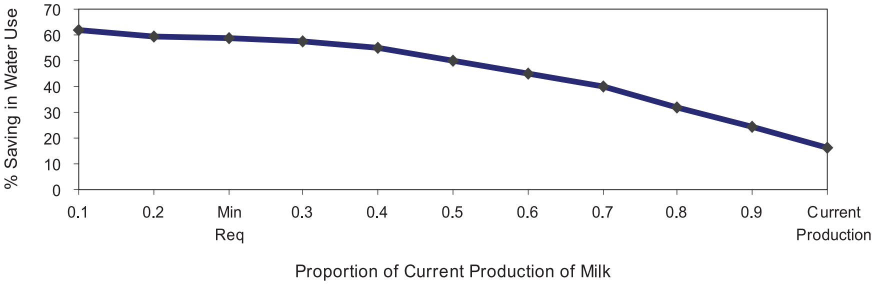
The North Gujarat Case

A standard approach to improve water productivity in agriculture (in order to save groundwater used in irrigation) would be the replacement of low water-efficient crops by those which are highly water-efficient. For North Gujarat, this would mean replacement of dairying by highly water-efficient crops such as orchards and cash crops like cumin. But, this would result in lower production of milk, the commodity which gives a stable income and regular cash flow for the farmers. Hence, it is a difficult option. Also, unlike in the case of agricultural crops, it is much easier for farmers to maneuver the inputs such as dry fodder and green fodder in his farm, though at the regional level it might be difficult for the farmers in the entire region to import fodder. Now, at the regional level, replacement of dairying by cash crops and orchards would have significant impact on the region’s milk production, which not only sustain its rural economy, but also produces surplus for export to other deficit regions.

In order to analyze the opportunities and constraints for improving regional water productivity in agriculture and to save irrigation water, farm economy in four talukas (sub-regions) of Banaskantha District in North Gujarat were simulated using linear programming. The results from two different optimization models, minimization and maximization models, for all the four talukas were more or less similar. Results from Vadgam taluka of Banaskantha District of North Gujarat showed that the volume of groundwater used for agriculture can be reduced to an extent of 49.5 % through the introduction of cumin or lemon. This would not affect the initial level of net farm income or compromise the food security needs of the region's population. However, while doing this, the milk production would undergo a sharp fall. This is because milk production was relatively more water intensive, and any effort to cut down groundwater use meant reducing milk production and substituting it with crops that are highly water productive.

With the introduction of water-saving technologies (WSTs) for field crops including alfalfa, the extent of reduction possible in groundwater use was higher (60.1 %), with lower extent of reduction in milk production. The net farm output would not be adversely affected by this. Further analysis showed that using WSTs, the groundwater use could be brought down by 17.5 %, if milk production in the region is to be maintained at the previous level. As Figure 1 (source: Kumar 2007) shows, the extent of reduction possible in groundwater use reduces with reduced willingness to compromise on milk production. This means that, the amount of leverage available for enhancing regional water productivity and cutting down groundwater use for farming becomes limited, if the income from dairy production as a percentage of the total farm income has to be high.

Figure 1. Milk production and aggregate groundwater use with WST (Vadagam).



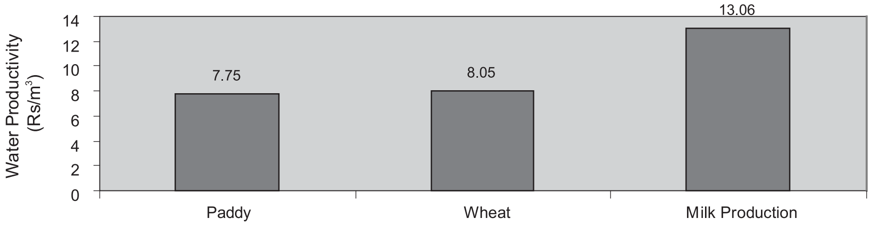
The adoption of orchard crops and drip irrigation systems involves risk taking by farmers. This is due to the need for finding markets in the first case, and the capital intensive nature of the system in the second case. Hence, the small and marginal farmers would show great resistance to adopting such systems. Thus, there is a trade off between enhancing water productivity of the farming system through crop and technology selection and reducing farming risks.

The Punjab Case

Let us examine the farming system interactions in western Punjab. Punjab's rice-wheat system of farming has been under criticism for causing low efficiency in resource use, low productivity of water use (Singh and Kalra 2002) and the problems of groundwater overdraft. It is established that many fruit crops have higher water productivity (Rs/m^3) than the conventional cereals such as wheat and paddy in arid areas. For instance, pomegranate grown in North Gujarat gives a net return of nearly Rs 40,000 per acre (i.e., USD900/acre) of land against Rs.8,000 per acre (i.e., USD180/acre) in the case of wheat. The WP is approximately Rs.100/m^3 for pomegranate (with an estimated annual water application of 90 mm) against Rs.4.46/m^3 for wheat. Also, there are crops such as potato, tomatoes, cumin, cotton and groundnut which are more water-efficient than rice and wheat, which can be grown in Punjab. Farmers from this region have already started shifting to high-valued cash crops in a moderate way.

But, there are limits to the number of farmers who can take up such crops due to the volatile nature of the market for most of these crops, their perishable nature and the high risk involved in producing them.[3] Also, the investments for crops are very high, demanding risk-taking ability. But, the extent to which farmers can allocate water to economically efficient crops would perhaps be limited by the need to manage fodder for animals. It may also get limited by the poor market support for orchard crops. Many farmers in Punjab and other semi-arid parts of India, manage crops and dairy farming together. Recent analyses from western Punjab seem to suggest that the overall net water productivity in rupee terms gets enhanced when the by-products of cereal crops are used for dairy production (see Figure 2). Water productivity in dairying was found to be higher than that of wheat and paddy (Kumar et al. forthcoming).

Figure 2. Water productivity in crops and milk production in western Punjab.



The equation presented in the earlier section explains this phenomenon. Unlike in the case of North Gujarat where dairying is very intensive, farmers in Punjab practice it as a complementary activity to crop production, where animal feeding depend mostly on crop residues such as wheat hay and paddy straw. They also do not grow highly water-intensive fodder crops like alfalfa. Water productivity (in kg/m^3 of water) for these by-products is very high.

This means that potential trade off exists between maximizing field level water productivity through crop shifts and maximizing water productivity at the level of the farming system. The possibility exists for simultaneously enhancing both field and farm level water productivity through the introduction of high-valued crops such as vegetables and fruits if those crops

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[3] The markets for fast perishing vegetables are often very volatile, and prices vary across and within seasons. The problem of price fluctuations is also applicable to cotton grown in western Punjab, which has high water productivity.

have water productivity values higher than those in dairy production.[4] However, in both cases, the risk involved in farming might increase. The reasons for this risk factor are the highly volatile nature of vegetable prices and the high chances of drastic price increases, or fodder scarcity, in the event of a drought. It has been found that while the normal price of dry fodder such as wheat hay and paddy straw is Rs. 1 per kilo, it goes up to Rs. 4 per kilo during the drought years.

Now, at the regional level, attempts to adopt water-efficient crops or crop-dairy based farming to enhance agricultural water productivity might face several socioeconomic constraints. National food security is an important consideration when one thinks about crop choices. Punjab produces surplus wheat and rice and supplies them to many other parts of India, which have food deficits, including eastern India (Amarasinghe et al. 2007; Kumar et al. 2007). Twenty percent of the country's wheat production, and ten percent of its rice production comes from Punjab; it contributes 57 percent and 34 percent, respectively to the central pool of grains for public distribution (Kumar et al. 2007).

Labor absorption capacity of irrigated agriculture and market prices of fruits are other considerations. Paddy is labor intensive, and a high percentage of migrant laborers from Bihar work in the paddy fields of Punjab. As per our estimates, 2.614 million ha of irrigated paddy in Punjab (as per 2005 estimates) creates 159 million labor days during the peak kharif season. The total percentage of farm labor contributed by migrant laborers during peak season was reported to be 35 % as per the Economic Survey of Punjab 1999-2000. Based on these figures, we have estimated that the total number of labor days contributed by migrant laborers to paddy fields in Punjab to be 55.75 million (Kumar and van Dam, Paper 6 of this book).

Replacing paddy by cash crops would mean a reduction in farm employment opportunities. On the other hand, the lack of availability of labor and fodder would constrain intensive dairy farming to maximize farming system water productivity at the regional level, though some farmers might be able to adopt the system. Large-scale production of fruits might lead to price crashes on the market, and farmers loosing revenue unless sufficient processing mechanisms are established. Hence, the number of farmers who can adopt such crops is extremely limited.

The Contrasts between North Gujarat and Punjab

Comparison of North Gujarat and western Punjab shows that even under similar climates, the routes to enhance water productivity and impacts of such initiatives on the farmers at the household level and on the socioeconomic system would be different, depending on the nature of the farming system. In the case of North Gujarat, water productivity improvement calls for replacing dairy farming with cash crops, and use of micro-irrigation systems for conventional crops. In Punjab, paddy-wheat system needs to be replaced by crops with higher water productivity than that in livestock farming, and dairying needs to be continued with imported fodder. Again, the possibility for import of fodder from the neighboring region of eastern India appears bleak, as these regions are net importers of food grains and have very little arable land. Haryana, while being an agriculturally prosperous region practices intensive dairying as well.

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[4] Otherwise, if the water productivity values of newly introduced crops is not higher than that of dairying, but higher than that of cereals, then fodder will have to be imported to practice dairying.

Introduction of cash crops in the farming system of North Gujarat would have adverse impacts on the stability of farm income and cash flow to farm households, though not on self-sufficiency in cereals. On the contrary, in the case of western Punjab, adverse impacts will be manifest in regional food security, employment and risks in farming. What appears is that in spite of the differences, integrating socioeconomic concerns such as food security, reducing risk in farming, and improving livelihood opportunities through agriculture; the opportunities for improving water productivity in agriculture to save water for the environment is extremely limited.

Now there are many semi-arid and arid regions in India, where dairying is emerging as a major source of livelihood in rural areas. They include western Rajasthan and peninsular and central India. These are also regions which are facing problems of groundwater over-draft. It is difficult to conclude that in semi-arid and arid regions, dairying would lead to further depletion of groundwater on the basis of the North Gujarat experience. In composite farming systems like the one in western Punjab, where dairying compliments cereal production, reasonably high levels of water productivity could be achieved in dairying. Such complementarity is due to the large area under crop production in per capita terms and the available crop residues being sufficient to feed livestock. Hence, it does not exert any additional pressure on local water resources.

Nevertheless, other opportunities for reducing pressure on groundwater through water productivity improvement in agriculture would be extremely limited if the region contributes significantly to national food security, rural employment etc. Also, there are limits to intensifying dairy production in such regions. The reason is that if dairying is made intensive, with fodder crops grown specially instead of being managed from crop residues, it would become water-intensive. In that way, it can induce additional pressure on local groundwater resources. But there are some ways to reduce the pressure on groundwater. They could include: enhancing water productivity of individual crops, including those used for dairying through micro-irrigation, which will also make milk production less water-intensive.

Can Dairying Thrive in Water-rich Regions of India?

There are large areas in India which are falling under humid and subhumid climatic conditions, including Kerala, north-east, the western and eastern Ghat regions and the Sub-Himalayan region. These regions have high rainfall and humidity, and low evaporation and evapotranspiration. Such regions also indulge in dairy farming. These regions have a lot of naturally grown grass that provide nutritious fodder for livestock. They also get dry fodder from residues of crops, particularly paddy. The advantage of such regions is that not only would the consumptive use of water by fodder crops be less, but most of such water needs would be directly met from precipitation. This is evident from a study conducted in Palakkad District of Kerala. It shows that green grass accounts for 84 to 95 % of the total green fodder fed to livestock.

This has a big impact on the irrigation water used for green fodder that is fed to cattle. It was found to be in the range of 40 to 160 liters per day per animal (Table 4). As a result, the effective water productivity in milk production (physical) was higher than that in the semi-arid North Gujarat. The study estimated effective irrigation water productivity in milk production to be 0.50 liter/m^3, 0.74 liter/m^3 and 0.51 liter/m^3, respectively, for buffalo, crossbred cow and indigenous cow (Table 4). As Table 4 shows, though the actual irrigation water productivity in milk production is much lower than these figures, a significant part of the water used up in milk

Table 3. Average feed and fodder fed to livestock in Palakkad, Kerala (kg/day/animal).

Name of Feed and Fodder	Average Daily Input (kg) for		
	Buffalo	Crossbred Cow	Indigenous Cow
A. Green Fodder	16.00	15.59	12.17
1 Local Green Grass	13.37	14.05	11.59
6. Maize	2.64	1.54	0.58
B. Dry Fodder	11.75	11.39	10.63
1. Paddy Straw	11.75	11.39	10.63
C. Concentrate	3.37	3.34	2.59
1. Balanced Cattle Feed	1.57	1.73	1.12
2. Cotton Seed Cake	0.38	0.44	0.25
7. Wheat Bran	0.43	0.66	0.28
8. Rice Bran	0.99	0.51	0.94
D. Drinking Water (Lt.)	0.034	0.029	0.023

Source: Rajesh and Tirkey (2005)

Table 4. Total water use and water productivity in milk production, Palakkad, Kerala.

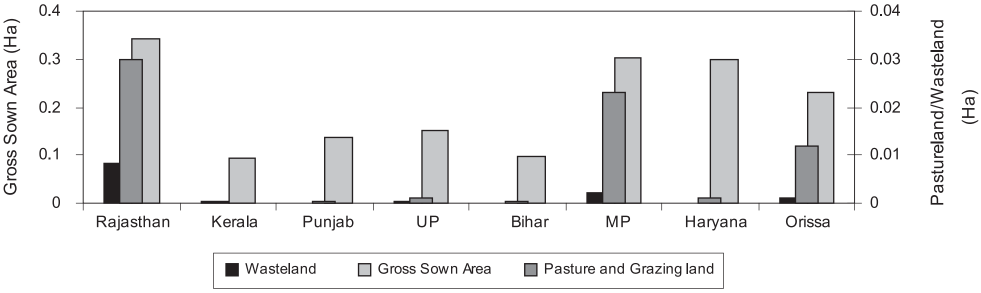
Particulars	Kerala		
	Buffalo	Crossbred Cow	Indigenous Cow
1. Green Fodder (m^3)	0.16	0.10	0.04
2. Dry Fodder (m^3)	4.73	4.59	4.28
3. Concentrate (m^3)	4.67	4.06	3.87
4. Drinking Water (m^3)	0.034	0.029	0.023
5. Total Water Used (m^3)	9.60	8.77	8.21
Milk Production (Liter/day)	2.46	3.49	2.36
Irrigation Water Productivity (IWP) (liter/m^3)	0.26	0.40	0.29
Effective IWP in Milk Production (liter/m^3)	0.50	0.74	0.51
IWP in Milk Production (Rs/m^3)	0.51	0.90	0.74
Effective IWP in Milk Production (Rs/m^3)	1.00	1.88	1.55

Source: Rakesh and Tirkey (2005)

production is the water embedded in the cattle feed. It was found to be 48.7 %, 46.2 % and 47.1 % of the total water used for milk production, for buffalo, cross bred cow and indigenous cow, respectively (see Table 3). Since local water resources are not used for their production, and are available from imports, they are not considered while estimating water productivity.

Furthermore, the cost of production of fodder was found to be negligible, when compared to that of cattle feed. It worked out to be 10.6 %, 8.9 % and 13 % of the total input cost, for buffalo, cross-bred cow and indigenous cow, respectively. The water productivity in economic terms was also relatively higher when compared to North Gujarat. The estimated effective irrigation water productivity was Rs.1.0/m^3, Rs.1.88/m^3 and Rs.1.55/m^3 for buffalo, cross -bred cow and indigenous cow, respectively (see Table 4)—(Rajesh and Tirkey 2005). Groundwater depletion due to agricultural withdrawal is not a problem in these regions. But, the amount of land available for dairy farming is a major constraint for increasing dairy production in the region. While per capita land availability is high in semi-arid regions, it is extremely low in humid and subhumid regions. The data on per capita gross sown area, per capita pasture land and per capita wasteland in eight major Indian states are given in Figure 3. The per capita land available in common lands (wasteland and pasture land) and cultivated area in semi-arid to arid Rajasthan is 0.454 ha and it is 0.30 ha in Haryana. Against these, the figure is only 0.094 ha in Kerala (see Figure 3).

Figure 3. Per capita land availability under different classes in selected states of India.



Summary of Findings

Water intensity of milk production is determined by the nature of dairy farming and not by climate alone. It is low water-intensive in regions where cereal production compliments low levels of dairy production, which minimizes the amount of irrigated green fodder used. The case of Punjab demonstrates this. When dairying is practiced intensively, production of irrigated green fodder becomes compulsory to sustain such high levels of inputs required to maintain high levels of production. This makes dairy production highly water-intensive as demonstrated by the North Gujarat case. In subhumid regions like Kerala, milk production is highly water-efficient, and it induces no pressure on local water resources as it is sustained largely by green grass that is naturally available and residues from crop production.

In semi-arid and arid areas where intensive dairy farming is practiced, replacement of dairy farming by highly water-efficient orchards and cash crops would be the major route to enhance water productivity in agriculture and also save some of the water used in agriculture, without adverse consequences for the economic prospects of farming. But, concerns of ensuring stable farm income and cereal security would limit our ability to shift from dairy farming to highly water-efficient crops. The best way to improve agricultural water productivity without adverse effects on farm income, food security and resilience of farming would be to make dairy production more water-efficient through efficient irrigation technologies for all crops that are amenable to the technology, including those having by-products, which are used as dairy inputs.

There are other semi-arid and arid regions like Punjab, which produce surplus cereals for food deficit regions. Rice-wheat system of production accounts for a major portion of the irrigation water used, and is mainly responsible for groundwater over-draft in this region. Since this region is not a major contributor to India's 'milk bank', decline in milk production in this region won't pose any major challenge to the country's nutritional security. But, any attempt to replace wheat and paddy should consider such crops which have higher water productivity than that in dairying. The reason is dairying, which cereal production sustains, yields much higher water productivity than those cereals themselves. Again, the scope for introducing crops which are more water-efficient than dairying, like orchards, would be constrained by concerns of regional food security and labor absorption in agriculture.

Conclusions

Dairying is emerging as a major economic activity in rural India. One reason for the increasing preference among farmers for dairying over other crops is the growing demand for milk and other dairy products, the relatively stable market and the ability of farmers to manage the inputs for dairying through feed and fodder imports in the face of water scarcity. In semi-arid and arid areas, the pressure dairying can put on water resources would depend on the levels of water productivity achieved in dairying, the intensity of dairying and what portion of the animal feed and fodder are produced in the locality. As analyses presented in this paper suggest, the water intensity of dairy farming could be remarkably different between regions of the same agro climate, depending on the intensity of dairying vis-à-vis the number of dairy animals that have to be supported by the available cultivated land.

The most desirable situation is one in which crops compliment dairy farming. Such a situation is possible when the number of cattle per unit of cultivated land is relatively low. This ensures that greater quantities of dry fodder are available from crop residues. In such situations, overall water productivity of the farming system would be reasonably higher. There are no easy ways to increase milk production in such regions without making it water-intensive, but that would cause further depletion of groundwater reserves in those regions. Again, such options are applicable to areas, which have extra arable land that can be brought under cultivation. However, this is not applicable to Punjab which already has high cropping intensity. The difficult option would be to engage in large-scale import of dry and green fodder, but subhumid and humid regions in India are not able to produce surplus fodder that can be exported to these regions.

The most undesirable situation for semi-arid regions is the intensification of dairy farming that depends on irrigated fodder crops locally, other than those obtained from agricultural crops as this would mean high water-intensiveness of milk production. Such a situation is possible when the per capita arable land is very low. In such cases, the opportunities for improving regional water productivity, which do not adversely affect milk production, need to be explored. The idea is to save some water for the environment without affecting the socioeconomic conditions of the communities who depend on it. This is in view of the fact that demand for dairy products is still increasing in India, and the country cannot afford to allow a decline in milk production. The options include: a) improving water productivity of crops, including those used in milk production, through the use of micro-irrigation; and b) replacement of existing low valued crops with high-valued orchard crops. For achieving these, promoting drips through subsidies could be one step, particularly for those fodder crops which fetch lower market value. The other step would be creating good marketing and processing facilities for fruits.

The subhumid and humid regions offer great potential to produce milk without depleting local water resources. The biggest constraint in such areas, however, is making milk production more intensive in spite of limited land availability. Unfortunately, such regions in India have much less crop land, pasture land and wasteland, which can supply biomass for dairy production. In a nutshell, intensive dairy farming is likely to pick up in semi-arid and arid areas, which have sufficient arable land. Such intensity, however, won't be ecologically sustainable and, as such, would eventually result in the depletion of local water resources. In such regions, efforts should be made to make it more water-efficient through the use of micro-irrigation systems for the crops, including water-intensive forage crops. While ecologically sustainable dairy farming is possible in subhumid and humid areas, there are major constraints to boosting milk production in those regions.

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Improving Water Productivity in Agriculture in India: Beyond ‘More Crop per Drop’

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Introduction

Water productivity in agriculture would be the single most important factor driving water use globally in the future (Molden et al. 2000; Rijsberman 2004). Hence, research to evaluate crop water productivity and analyze the drivers of change in the same, has fascinated many researchers and scholars worldwide (Ahmad et al. 2004; Ambast et al. 2006; Grismer 2001; Howell 2001; Kijne et al. 2003; Zwart and Bastiaanssen 2004; Singh 2005; van Dam et al. 2006). As a result, most of the research studies on crop water productivity were undertaken in naturally water-scarce regions of the world. Such regions include western United States, drought-prone areas of arid Australia, semi-arid areas of Punjab State in India, Punjab Province in Pakistan, Turkey and Mexico.

Water productivity in crop production can be expressed in terms of biomass production per cubic meter of water diverted or depleted (kg/m^3), known as physical productivity of water; and net or gross present value of the crop produced per cubic meter of water diverted or depleted (Rs/m^3) known as economic productivity of water (Kijne et al. 2003).

Definition of water productivity is scale dependent (Molden et al. 2003). Water productivity can be analyzed at the plant level, field level, farm level, system level and basin level. According to the scale, the determinants of water productivity would also change. Analyzing water productivity at the plant level would require knowledge of the total biomass per unit of water transpired, and doing the same at the field level would require knowledge of crop yield (kg/ha) or net return from crop production (Rs/ha) against the total amount of water applied or unit of water depleted. Whereas, analyzing water productivity at the farm level would involve the net return from the entire farm against the total water diverted or depleted. The reason is that, as Rothenberg (1980) notes, farmers grow a variety of crops within their farm, and sometimes in combination with dairy farming, which depends on crop residues as inputs. But, if water productivity has to be analyzed at the level of the irrigation system or the river basin, it has to be in relation to the total amount of water depleted rather than the total amount of water diverted. The reason is that not all the water diverted for irrigation would be depleted, and instead might be available for reuse in the form of recharge to groundwater, which can be pumped out by the downstream well irrigators (Allen et al. 1998) or residual moisture in the soil profile available for the next crop.

Again, water productivity can be analyzed for one season or for the entire crop cycle, thereby changing the time scale of analysis. Accordingly, the value of the denominator of water productivity, i.e., 'depleted water' would change. This is because of the following reason. The residual moisture available in the soil might get treated as nondepleted water in a crop-wise analysis. But this soil moisture might eventually get depleted in soil evaporation during the fallow period, and therefore get included in the denominator if the entire annual crop cycle is considered for analysis. This also means that the farm level water productivity analysis should consider the entire crop cycle to capture this time-scale effect.

The classical concept of irrigation efficiency used by water engineers to analyze the 'productive use' of water, omitted economic values (Van Dam et al. 2006) and looked at the actual evapotranspiration (ET) against the total water diverted for crop production (Kijne et al. 2003). Over and above, it does not factor in the 'scale effect' (Ahmed et al. 2004; Van Dam et al. 2006). In the recent past, there have been major advancements in the theoretical discourse on ways to assess how productively every unit of water is used up in crop production, leading to more comprehensive definitions of water productivity.

A recent synthesis of available literature by Zwart and Bastiaanssen (2004) of showed that, water productivity in terms of biomass output per unit of depleted water (kg/ET) or physical productivity of water in crop production has been mostly analyzed across the world at least for some of the major crops; and enough is already known about the factors that explain its variations across locations. But, it also showed that no attention is paid to know how the crops compare in terms of economic returns from every unit of water depleted. But, this is crucial, because the measures to enhance water productivity of a crop such as higher dosage of nitrogenous fertilizers; improved soil management; better agronomic practices, including the use of high yielding varieties, and pest control; water harvesting and supplementary irrigation; and investment in water delivery control measures, have economic imperatives.

The reason for this heavy focus on the physical productivity of water is most of these analyses were done by agricultural scientists, who are concerned with raising the dry matter yield of crop per unit of evapotranspiration. The other factors, which might have been responsible for this bias are: 1) water is a limiting factor at the societal level for enhancing crop production in these regions (Howell 2001), which still have large cropped areas under unirrigated conditions (Loomis and Connor 1996: pp10), and water productivity improvement enables farmers to divert part of the saved water to expand the irrigated area; and, 2) with volumetric rationing and the prices that farmers have to pay for water, they are likely to get higher net returns along with higher yields through efficient irrigation technologies that reduce consumptive use.[1] Another factor could be the fluctuating price of agricultural commodities in the market, which changes the net return per unit volume of water.

But, the avenues to improve agricultural WP through farming system changes are not explored. This is a major shortcoming when we consider the fact that most of the farms in developing economies like India and most of Africa are complex with several crops; and also

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[1] As water saving leads to cost saving in irrigation sufficient to offset the additional cost of fertilizer and technology inputs.

composite with crops and dairying instead of one or two crops. After Rothenberg (1980), as farms are organized to maximize net economic return, they are the best fundamental units for economic analysis. Hence, how productively farmers use their water cannot be assessed in relation to a particular crop alone, but in relation to the entire farm. In sum, this dominant paradigm of 'more crop per drop' certainly does influence WP research in Asia and Africa.

On the other hand, there has also been a greater recognition of the distinction between securing field level 'water-saving' and field-level WP improvement, and water-saving and WP improvement at the basin-scale (Allan et al. 1998; Howell 2001; Molle and Turral 2004; Seckler et al. 2003). The concept of 'open basins' and 'closed basins' is often used to explain how the determinants of WP could be manipulated and water saving achieved, or otherwise, in different situations. The information obtained discloses that in 'closed basins', field-level water saving does not result in water-saving and WP improvement at the basin level, except when the return flows meet with saline aquifers or are nonreturnable; and otherwise basin level water saving and WP improvements comes only from a reduction in consumptive use (Molle and Turral 2004).

This new paradigms in water resource management also seems to have influenced research in many countries in Asia and Africa: 1) in deciding what one should look for as key 'determinants' in WP analysis; and; 2) in identifying the drivers of change in WP. They have hardly captured the complex technical, social, economic, institutional and policy settings that govern water allocation policies by the government and water use decisions by the farmers. This concerns the poor technical efficiency and reliability of public canal systems; heavy subsidies in pricing of water and electricity in the farm sector; huge public investments in water harvesting; and, lack of institutional regimes governing the use of water from canal schemes and groundwater.

The overarching objective of this paper is to have a critical look at these two paradigms in agricultural water management to see how far they are useful in exploring new avenues for WP improvements and water saving, particularly in situations like India. It also explores new opportunities for WP improvements and water saving for fields, farms and regions, by analyzing the complex variables which drive these WP parameters, and also identifies new areas for research.

Some of the specific research questions being addressed in this paper are as follows.

1. Given the heavy subsidies in electricity and water used for agriculture and lack of well-defined rights in surface water and groundwater in developing countries like India, does research on raising 'crop per drop' make sense, or what should be the new determinants of WP for both farmer and basin water managers?

2. What considerations should be involved in analyzing basin level WP and water saving impacts of efficient irrigation?

3. What are the likely impacts of improved reliability of irrigation, and changing water allocation on crop water productivity and water saving?

4. What are the opportunities and constraints for improving agricultural water productivity at the level of farming systems?

5. What should be the priority areas for research on enhancing regional WP in agriculture, in countries like India where food security, rural employment and poverty alleviation are still major issues?

Why a New Paradigm of Research on Agricultural Water Productivity in India?

More Income Returns versus More Crop Per Drop

The main consideration involved in analyzing WP in the West is reducing the amount of water required to produce a unit weight of crop, as this would automatically ensure higher net return per unit of land. But this is not the concern in many developing economies in Asia, where land use intensity is already very high in many regions. Surface water is heavily subsidized, and pricing is also inefficient (Kumar 2003). There is zero marginal cost of electricity used for pumping groundwater for irrigation (Kumar 2005). Hence, the measures to enhance water productivity through ET reduction and yield enhancement may not result in significant improvement in net income for the farmer for a unit area of irrigated land, though net water productivity in rupee terms may increase. While major investments are required to achieve irrigation efficiency improvements and yield enhancement, the increased benefit farmers get is only in terms of market price for higher yield. The reason is that the real water-saving and energy saving,[2] which are major impacts of technological interventions, do not get converted into savings in private costs of water.

Enhancement in WP (kg/ET) in field crops like wheat can mainly come from crop technologies. A study by Sander Zwart (2006), which involved analysis of system level WP in irrigated wheat in six different regions around the world using SEBAL (Surface Energy Balance) methodology, shows that the variation in WP is not so much due to variations in ET, but due to variations in the yield (see Table 1). The average ET was highest in Pakistan (443 mm) and lowest in Sirsa (361 mm), which is approximately 10 % higher/lower than the average (source: analysis by Sander J. Zwart 2006). Though the potential evapotranspiration (PET) depends on the climate, especially the relative humidity (air temperature and solar radiations remaining in

Table 1. Average system-level water productivity in wheat in six different wheat growing regions around the world.

Location	Average ET/Standard Deviation (mm)	Average Yield (tonne ha^{-1})	Average WP_{ET} (kg m^{-3})
Nile Delta, Egypt	408 (59)	6.1 (0.9)	1.50 (0.12)
Yaqui Valley, Mexico	402 (36)	5.5 (0.9)	1.37 (0.16)
Sirsa, India	361 (16)	4.4 (0.3)	1.22 (0.06)
Linxian County, China	436 (35)	3.8 (1.4)	0.86 (0.28)
Hebei Province, China	380 (50)	2.5 (0.9)	0.64 (0.21)
Sindh Province, Pakistan	443 (82)	(2.2 (0.7)	0.50 (0.11)

Source: Analysis by Sander J. Zwart dated May, 2006

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[2] Whether use of efficient irrigation technologies can reduce or increase energy use for irrigation depends on the type of irrigation technology and the extent to which the traditional water supply is pressurized (Loomis and Connors 1996).

a narrow range across these six regions), actual ET could have been manipulated by changing the water available to crops through irrigation. But, this does not seem to have happened. The reason that ET remains the same is that there is a shift from evaporation (E) to transpiration (T), which leads to greater biomass production. As soon as the environment for crop production is improved (fertilizers, weeding, better seeds, water management, etc.,) there will be a shift from non-beneficial to beneficial water depletion. This, of course, requires farmer investments.

Now, the only way to create an incentive among farmers to adopt efficient irrigation technologies for WP improvement is to subsidize it. The idea is to make private benefits offset the private costs (Kumar 2007). While yield enhancement is also a benefit of efficient irrigation technologies (Loomis and Connor 1996: pp 398), it can also come from improved agronomic practices mentioned above. The extent of subsidy for a system which can save 'X' amount of water could be kept higher than the difference between the private costs and benefits. It should be guided by the positive externality that 'X' creates on society.

But, government subsidies for efficient irrigation technologies are extremely limited in countries like India. For instance, the Government of India had provided Rs.5 billion towards subsidy for drip and sprinkler systems in the eleventh 5-year plan. But, this amount is just sufficient to cover an area of 100,000 ha against a total net irrigated area of nearly 55 m ha, accounting for just 0.20 %, if one considers an investment of Rs.100,000 per ha of area under MI system, and a subsidy to the tune of 50 %. Hence, such measures to enhance WP do not result in increased land productivity. Under the much-publicized Andhra Pradesh Micro-Irrigation project of the Government of AP, a total area of 166,100 ha was covered under MI systems over a time period of nearly 30 months. The total subsidy benefit to farmers was to the tune of 209.96 crore rupees, meaning Rs.18,070 per ha. The result is that most of the farmers have installed drip systems for horticultural crops, for which returns would anyway be high even without drips[3] and sprinklers, which are low cost but not technically efficient for small farms (Kumar et al. 2008). If adoption is limited to horticultural crops, which cover small areas in India, the potential of MI systems in WP enhancement would further be limited.[4]

This means that if MI system is used for conventional crops, the farmers have to divert part of the water saved to another plot to sustain their income as net return is WP multiplied by the volume of water. However, in situations where the entire holding is already used, farmers will not have much incentive to go for measures that do not increase their returns from the land but only increase their returns per unit of water. This is the situation in India, where the average holding of farmers is quite low (less than 1 ha) when compared to that in western US or Australia. The size of median landholding in Australia is 300 ha (ABS 2002). This clearly means that what is socially optimal is that farmers look for alternatives that enhance the productivity of their land remarkably, simultaneously reducing the water requirement, or diverting part of the water to other water-based farming systems that have minimal dependence on land. In a nutshell, there is a clear trade-off between enhancing the physical productivity of water, and maximizing income returns. This argument also holds true when it comes to

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[3] This was noted by B. D. Dhawan way back in 2000 in an article titled 'Drip Irrigation: Evaluating Returns' (see Dhawan 2000).

[4] Kumar et al. (2008) estimated that the overall potential of MI systems in India is only 5.8 m ha, which is far less than the figures estimated by Government of India's task force on MI.

analyzing the WP impacts of water harvesting for supplementary irrigation, which is analyzed in the case of public investments. This is dealt with in the subsequent section.

Poor Focus on Economics of Water Harvesting and Supplementary Irrigation

In the west, the focus in WP research has been on efficient irrigation technologies, including those for supplementary irrigation. However, in some African countries (Oweis et al. 1999; Rockström et al. 2002), Mexico (Scott and Silva-Ochoa 2001) and in India, the focus has shifted to potential impact of water harvesting.

This is applicable to some of the recent work in eastern African countries. Rockström et al. (2002) have shown the remarkable effect of supplementary irrigation through water harvesting on the physical productivity of water expressed in kg/ET, for crops such as sorghum and maize. However, the research did not evaluate the incremental economic returns due to supplementary irrigation against the incremental costs of water harvesting. It also does not quantify the real hydrological opportunities available for water harvesting at the farm level and its reliability. The work by Scott and Silva-Ochoa (2001) in the Lerma-Chapala Basin in Mexico showed higher gross value product from crop production in areas with better allocation of water from water harvesting irrigation systems. But, their figures of surplus value product, which takes into account the cost of irrigation, are not available in their analysis. In arid and semi-arid regions, the hydrological and economic opportunities of water harvesting are often over-played. A recent work in India has shown that the cost of water harvesting systems would be enormous, and reliability of supplies from such systems would be very poor in the arid and semi-arid regions of India, which are characterized by low mean annual rainfalls, very few rainy days, high inter-annual variability in rainfall and rainy days, and high potential evaporation, leading to a much higher variability in runoff between good rainfall years and poor rainfall years (Kumar et al. 2006).

With the high capital cost of WH systems needed for supplemental irrigation, the small and marginal farmers would have less incentive to adopt such systems. In addition, the incremental returns due to yield benefits may not exceed the cost of the system. This is particularly so for crops having a low economic value such as wheat and paddy, which dominate arid and semi-arid regions in India. But, even if the benefits due to supplementary irrigation from water harvesting exceed the costs, it will not result in higher WP in economic terms in closed basins. The exception is when the incremental returns are disproportionately higher than the increase in ET. This is because, in a closed basin, increase in beneficial ET at the place of water harvesting will eventually reduce the beneficial use down stream. In countries like India, lack of this economic perspective in decisions, however, results in too much public investment towards subsidies to farmers to harvest water locally. To sum up, gain in crop per drop (kg/ET) cannot drive water harvesting for supplementary irrigation in semi-arid and arid regions. Also, incremental net benefit considerations can drive water harvesting at the basin scale only if there is no opportunity cost of harvesting.

Distinction between Consumed Fraction and Evapotranspiration

The real water savings through efficiency improvements at different scales had been thoroughly discussed by several scholars (Allen et al. 1998; Molle and Turral 2004; Molle et al. 2004; Seckler 1996). The main argument is that in 'closed basins', increasing efficiency would only reduce return flows and not reduce the depleted portion of irrigation withdrawals. Thus real water saving is not possible through improvements in irrigation efficiencies in closed basins (Molle and Turral 2004). While there are sufficient evidences on the relationship between ET and yield (Connor and Jones 1985; Grismer 2001; Rockström et al. 2002), at least a few scholars argue that reduction in consumed fraction and, therefore, 'real water saving', is not possible without reducing the yield, unless we use better crop varieties or agronomic practices.

But, these technologies might be able to reduce the consumptive water use as well as consumed fraction[5] (CF), without reducing the beneficial evapotranspiration (ET) and the yield (see page 76 of Allen et al. [1998] for details on ET and consumed fraction), thereby leading to 'real water savings' at the field level. Such reductions in consumption could be achieved through reduced evaporation from excessively wet soil, or reduction in nonreusable deep percolation from water application in excess of the soil moisture deficit in the root zone. However, the distinction between ET and CF is often not made in analyzing the impact of depleted water on yields. Hence, an automatic conclusion is that real water saving at the basin level is not possible without changing ET (Zhu et al. 2004), or affecting other uses in water-scarce basins (Molle et al. 2004). Whereas in reality, improvements in crop water productivity in physical terms and water saving might be possible at the basin level through efficient irrigation technologies. Hence, research on basin level WP impacts of efficient irrigation technologies should consider CF as a determinant.

Are There New Opportunities for Improving Water Productivity in Countries like India?

Opportunities for Improving Field-level Water Productivity

It is widely acknowledged that reliability and degree of control over field-level water allocation are, by and large, very poor in surface irrigation systems in India (Brewer et al. 1999; Meinzen-Dick 1995), leading to poor technical efficiencies (GOI 1999; Ray 2002). Whereas the irrigation systems in the USA and Australia are far more reliable and are designed for a high degree of water delivery control. Two major dimensions of irrigation service, which have significant impacts on crop yields are, timeliness of water delivery (Perry and Narayanamurthy 1998) and excess water deliveries, with the impact of first being positive and that of the second being negative, as illustrated by a study on irrigated rice production in Sone irrigation command in Bihar (Meinzen-Dick 1995). But, the opportunities available with improved reliability of irrigation and 'changing water allocation' in enhancing WP have not been examined.

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[5] See Allen et al. (1998) for a detailed discussion on various components of the applied water, such as consumed water, consumed fraction, beneficial transpiration, non-beneficial evaporation from the soil and non-recoverable deep percolation.

Impact of Quality and Reliability of Irrigation on Water Productivity: This research is particularly more important when there are theoretical (Malla and Gopalakrishnan 1995; Perry 2001a) as well as practical issues involved in using pricing as a tool for demand regulation (de Fraiture and Perry 2004; Perry 2001a). But, the task also lies in developing quantitative criteria for assessing quality and reliability. Kumar, Trivedi and Singh (this book) had developed an index, named 'Irrigation Quality Index' for assessing the quality and reliability of irrigation water at the field scale. Implicitly, its application is limited to fields-scale assessments only, where the crops remain the same. The same cannot be extended to farms where the crops change.

There are evidences from different parts of the world that well irrigation results in higher yields than canal irrigation. Though there are sufficient evidences to the effect that well irrigators get a higher yield, and in spite of higher cost of irrigation get higher net returns as compared to canal irrigators (Kumar and Singh 2001; IRMA/UNICEF 2001), there is limited research data on the differential economic productivity of groundwater irrigation over surface irrigation. A recently published study for the Andalusian region (southern Spain) shows that each cubic meter of groundwater used for irrigation provides five times more money and almost four times more jobs than a cubic meter of surface water used for irrigation (Hernández-Mora et al. 1999).

However, the statement about higher reliability of well irrigation is not a universal one. In some canal command areas, particularly in their head reaches, reliability of water supply is found to be very high due to the availability of water throughout the season. Further, the chemical quality of surface water can sometimes be much better than that of well water due to the presence of minerals, which provide micro-nutrients for plant growth as the water comes from mountainous catchments through surface runoff (Kumar, Trivedi and Singh, this book). Against this, the well water can be of poor chemical quality, due to the presence of excessive salts in dissolved form, which can be harmful for soil health and, therefore, affect crop growth. This differential chemical quality of water can improve the overall quality of surface irrigation.

Nevertheless, well irrigation is generally of higher quality as compared to canal irrigation. But, in the case of well irrigation, the manner in which this positive differential reliability gets translated into WP gains is a major point of inquiry. There are two possibilities. First, it is an established fact that the crop yield increases in proportion to the increase in transpiration, and, at higher doses, irrigation does not result in beneficial transpiration, but in non-beneficial evaporation. Irrigation water dosages are normally higher in canal irrigation. This way, increased CF does not result in a proportional increase in the yield of crops (Vaux and Pruitt 1983). Non-recoverable deep percolation is another non-beneficial component of the total water depleted (CF) from the crop land during irrigation (Allen et al. 1998). This also increases at a higher dosage of irrigation, which occurs in the case of canal irrigation. Moreover, with controlled water delivery, efficiency of fertilizer usage would be better in the first case. Hence, with improved reliability and water delivery control, both the denominator (CF) and numerator (yield) of the water productivity parameter (kg/m^3) could be higher. This can be better understood by the negative correlation between surplus irrigation and crop yields in the Sone command where surplus irrigation led to reduced yields (Meinzen-Dick 1995). Since, there are no extra capital investments it would also lead to higher productivity in economic terms.

The second possibility is that with greater quality and reliability of irrigation, the farmers are able to provide optimum dosage of irrigation to the crop, controlling non-beneficial evaporation, and non-recoverable deep percolation. And as a result, the CF remains low and the fraction of beneficial evapotranspiration within the CF or the depleted water remains high. Also, it is possible that with the high reliability regime of the available supplies, even under scarcity of irrigation water, the farmers can adjust their sowing time so that they are able to provide much needed watering. This can bring out high yield responses. Both result in higher WP in kg/ET.

But, are the differences in WP in economic terms (Rs/m^3) caused by well owners growing more water-efficient and water-sensitive crops with assured water supplies? Evidence in support of this argument is found in a recent study comparing the water productivity of shareholders of tubewell companies and water buyers in north Gujarat. The study showed that the shareholders of tubewell companies got much higher returns from every unit of pumped water, i.e., overall net water productivity in economic terms (Rs.4.18/m^3), as compared to water-buyers (Rs.1.3/m^3). The reason was that water allocation for shareholders was quite assured in volumetric terms, and irrigation water delivery was highly reliable, owing to which they could budget water properly, select water-sensitive and high-valued crops and judiciously make investments for inputs; whereas water buyers were at the mercy of the well owners (Kumar 2005).

Now, with expanding well irrigation in many arid and semi-arid countries like India, including canal command areas, new opportunities for improvements in the reliability of water supplies are available. If well irrigation gives positive differential WP over surface irrigation, we can incorporate such features that contribute to higher water productivity in well irrigation in gravity irrigations systems as well. They include creating an intermediate storage system for storing canal water; and lifting and delivery devices for the stored water. That said, in real economics terms, what does the gain in productivity mean given the fact that the economic costs of irrigation is much higher than the private costs for both canal irrigation and well irrigation? Understanding these linkages will help design better policies for water allocation (whether to supply water by gravity or promote conjunctive use) and pricing in surface irrigation. If reliability results in higher WP (Rs/m^3) in well irrigation, which cannot be explained by price variations, then that makes tariff increase in canal water contingent upon improving the quality of irrigation.

Impact of Changing Water Allocation on WP and Water Saving: Water management decisions are often taken on the basis of average water productivity estimates. For the same type of system, water productivity for the same crop can change at the field scale (Singh et al. 2006: pp272) according to water application and fertilizer use regimes. Hence, it is important to know the marginal productivity with respect to water and nutrient use. It helps to analyze the role of changing water allocation strategies at the field level in enhancing WP. But, there are no data available internationally.

For a given crop, the irrigation dosage and the crop water requirement (beneficial use plus beneficial nonconsumptive use) corresponding to the maximum yield may not correspond to the maximum water productivity (Rs/m^3)—(Molden et al. 2003). The WP (k/m^3) would start leveling off and decline a lot before the yield starts leveling off (see Figure 1.2 in Molden et al. 2003). Ideally, WP in terms of net return from crop per cubic meter of water (Rs/m^3) should start leveling off or decline even before the physical productivity of water (kg/m^3) starts showing that trend. When water is scarce, there is a need to optimize water allocation to maximize water productivity (Rs/m^3) through changing the dosage of irrigation. But, this may be at the cost of reduced yield and net return per unit of land, depending on to which segment of the yield and WP response curves the current level of irrigation corresponds.

Recent analysis with data on applied water, yield and irrigation WP for select crops in the Narmada River basin in India showed interesting trends. In many cases, trends in the productivity of irrigation water in response to irrigation did not coincide with the trends in crop yields in response to irrigation (Figures 1 and 2); whereas in certain other cases, the trends in irrigation WP in response to irrigation and the trends in yield in response to irrigation did actually coincide at least for some range in irrigation (Figures 3 and 4). Knowing at what segment of the WP response curve the irrigation dosage to a given crop lies, helps understand how changing water allocation would change the crop yield and WP.

Figure 1. Yield vs Irrigation Dosage in Wheat (Hoshangabad 2002).

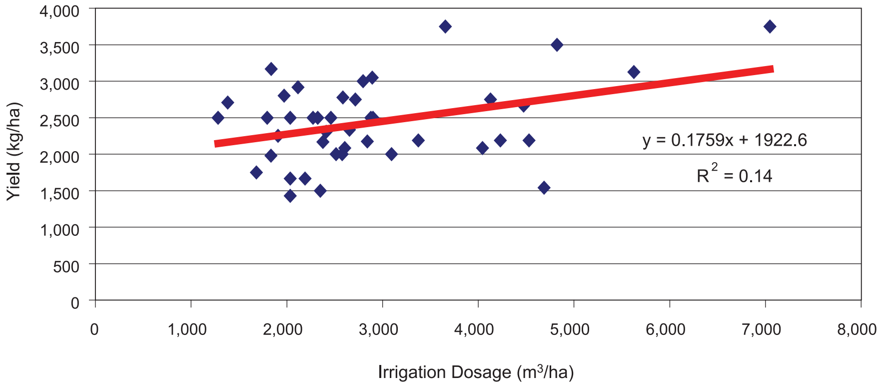
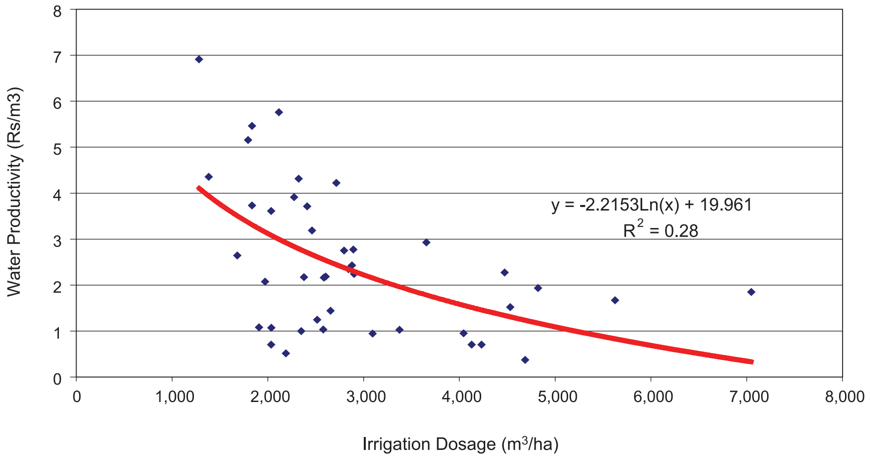


Figure 2. Water Productivity vs Irrigation Dosage in Wheat (Hoshanagabad 2002).



The regression values for the response of yield to irrigation dosage being very small (Figures 1 and 3), one could argue that many factors other than irrigation explain yield variations. But, the data that are presented here are for different farmers, who represent different soil conditions, different planting dates and different seed varieties, all of which have a potential to influence the crop yield. If one takes into account this, one could say that the actual yield response to irrigation would be much stronger if the planting date, soils and seed varieties are

Figure 3. Yield vs Irrigation Water Dosage in Cotton (West Nimar 2003).

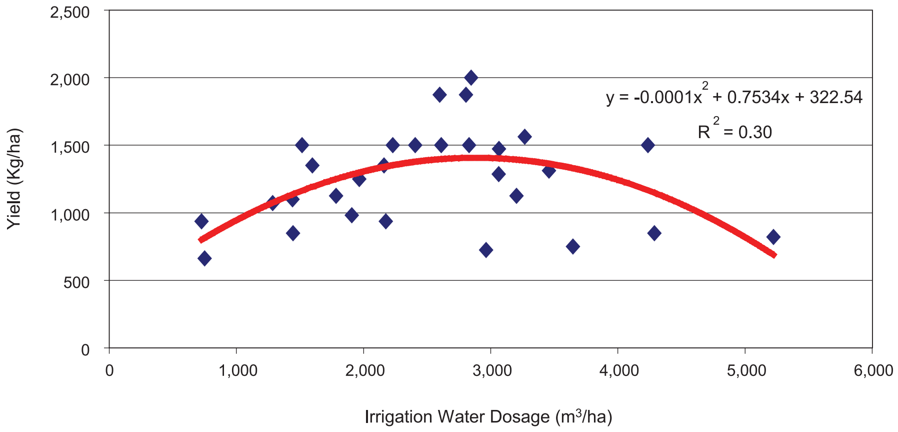
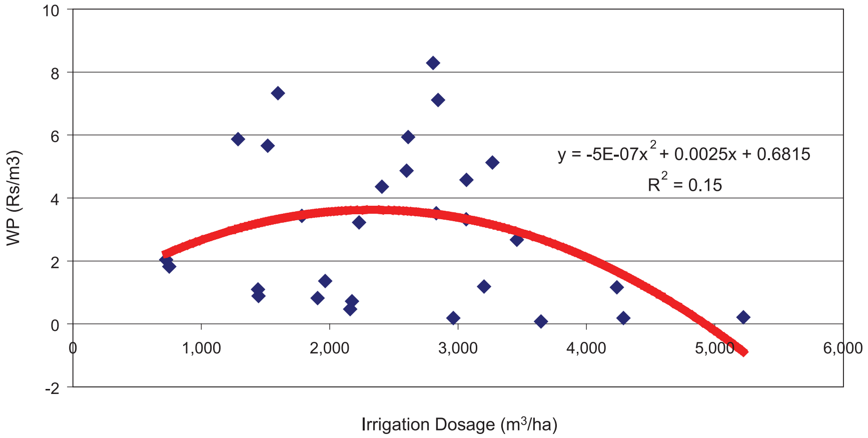


Figure 4. Water Productivity vs Irrigation Dosage in Cotton in (West Nimar 2003).



the same. Also, the slope of the yield curve is very mild in the case of Figure 1. This is quite contrary to what can normally be found given the wide range in irrigation water dosage among the sample farmers. This can be explained by the variation in PET, and the moisture availability across farmers in the sample, which changes the irrigation water requirements.

In the first case, where the level of irrigation corresponds to the ascending part of the yield curve, but to the descending part of the WP curve (Figures 1 and 3), then limiting irrigation dosage might give higher net return per unit of water. But, farmers may not be interested in that unless it gives a higher return from the land. Hence, if the return from the land does not improve, the strategy can work only under three situations: 1) the amount of water that farmers can access is limited by the natural environment, like limited groundwater reserves; 2) there is such a high marginal cost of using water, due to high prices for water or electricity used for pumping water, that WP is much closer to the values attained at the highest levels of irrigation; and, 3) water supply is rationed. In all these situations, the farmers should have extra land for using the water saved. Under condition of supply rationing, farmers would anyway be using water for growing economically efficient crops. But, the issue being addressed here is that for a given crop how far water productivity can be enhanced to a level that the best managed farms do achieve.

In all these three situations described above, the WP improvements would lead to farmers diverting the saved water for irrigating more crops to sustain or enhance their farm income. The reason is that the amount of water being handled by farmers is too small that they need to use the same quantum of water as previously since the WP differences are just marginal. This behavior of the farmer can better be understood from the following equation, which defines net improvement in farm income:

$$\text{Net change in farm income} = \{V - \Delta V\}^*\{\Phi + \Delta\, \Phi\}\text{-}V^*\, \Phi = V^*\, \Delta\Phi\text{-}\ \Delta V^*\{\Phi + \Delta\, \Phi\}$$

Where, ‘V’ is the volume of water diverted for irrigation prior to the adoption of productivity improvement measures; ΔV is the reduction in the volume of water diverted for irrigation after adoption (+ive); Φ is the productivity of water when volume V was used for irrigation; $\Delta\, \Phi$ is the rise in water productivity after adoption (+).

Analyzing the equation, the only way a small farmer can maximize his net farm return in the improved WP scenario is by making ΔV zero. In the case of a large farmer in US or Australia, who might use 100 to 500 times more water than an average farmer in India, there is still an option available for enhanced returns, even if he decides to reduce the volume of water used for irrigation (i.e., $\Delta V > 0$) because V is very large, making $V^*\, \Delta\Phi$ very large.

Hence, the impact would be greater economic outputs for the same quantum of water. Nevertheless, the impact can be different if the farmers get higher returns along with higher WP through changing water allocation as illustrated earlier. Hugh Turral[6] (per. com) argues that to achieve real demand regulation, water for agriculture needs to be formally allocated or re-allocated. If that means less water for agriculture, improving WP will be one of the responses. Howell (2001) cites the example of the Texas high plains. The increased use of irrigation technologies for wheat had resulted in the enhancement of water use efficiency (Kg/ET), which followed significant yield increase, in wheat (Table 8, Howell, 2001). He argues that in such situations, farmers would achieve real water saving. This could result in water saving at the system level, if the farmers do not expand the area under irrigation. But in this case, the farmers can afford to reduce the area under irrigation as the net return per unit of land also might have improved.

In the second case, where both the yield and WP curve are descending (Figures 3 and 4), the impact of change in water allocation on both WP and yield would be similar, i.e., reduced water allocation would result in both yield and WP gain. This is the most ideal situation where farmers have a strong incentive to become adapted to the water allocation strategies enforced by an official agency as in the case of canal irrigation, and voluntarily cut irrigation dosage in well irrigation. But, this is a situation which is not very common in semi-arid and arid conditions. Overirrigation is more common in rich alluvial areas like central Punjab and Haryana, where farmers get free electricity and canal water is heavily subsidized.

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[6] Formerly Principal Researcher, International Water Management Institute, Colombo, Sri Lanka.

For instance, analysis of soil water balance in rice-wheat fields in the Sirsa District of Haryana by Singh (2005) using the SWAP (Soil Water Atmosphere Plant) model shows that the total water applied was in excess of the estimated ET (in the order of 290 mm to 561 mm). Interestingly, the ET value was higher for the field which had a lower dosage of irrigation (see Table 2). It shows that there is ample opportunity for real water saving through a reduction in non-beneficial E of ET-the part of soil moisture storage change, which would eventually get evaporated from the field. By reducing irrigation dosage in such conditions as cited above, the farmers gain both higher land productivity (return per unit of land) and higher return per unit of water.

Table 2. Water balance in two rice-wheat fields in Sirsa, Haryana during kharif.

Field No.	Irrigation Dosage (mm)	Rainfall (mm)	ET (mm)	Groundwater Recharge (mm)	Soil Moisture Change (mm)
1	1,062	177	949	98	175
2	1,250	177	858	121	440

Source: Ranvir Singh (2005): Table 4.6, pp: 46

In the ultimate analysis, it may appear that to affect demand reductions, it is important to ration water allocation in canals along with changes in the practice of farmers by educating them on better crop management. Proper regional and sectoral water allocation can drive WP improvement. Experiences from the Murray-Darling Basin (Haisman 2003) and Chile (Thobani 1997) show significant improvements in water use efficiency and value of water realized, respectively, in irrigated production after the introduction of volumetric rationing enforced through properly instituted water rights. Nevertheless, marginal WP analysis of the kind presented above can help decide on the allocation and delivery strategies for canal water, provided farmers are quite aware of water allocation and irrigation scheduling policies.

Hence, there is much more one can achieve in WP enhancement and water demand management in gravity irrigation without resorting to water pricing options technically. As Perry (2001a) notes, assigning volumes to specific uses, and effectively rationing water where demand exceeds supplies, would be an effective approach to cope with water shortages. But, its actual potential might depend on the situation in terms of access to land and water, and the institutional and policy environment, such as water and energy prices and water rights regimes. It is clear from the foregoing analysis that water control can help achieve WP enhancement even without pricing and volumetric water rights, if there is a physical shortage of water or extra land for cultivation is not available.

The recent past has shown significant debates over the usefulness of irrigation water pricing as a way to regulate water demand. While, some argue for it (Malla and Gopalakrishnan 1995; Tsur and Dinar 1995; Johansson 2000), some others argue against it, pointing out shortcomings at both theoretical and practical levels (Bosworth et al. 2002; Perry 2001a). There are three major, and important contentions for those who argue against pricing: 1) questioning the logic in the proposition that "if the marginal costs are nil, farmers would be encouraged to use large quantities of water before its marginal productivity becomes zero, consuming much more than the accepted standards and needs" (source:

Molle and Turral 2004); 2) the demand for irrigation water is inelastic to low prices, and the tariff levels at which the demand becomes elastic to price changes would be so high that it becomes socially and politically unviable to introduce (de Fraiture and Perry 2002; Perry 2001a); 3) there are no reasons for farmers to use too much water, which can cause overirrigation (Molle and Turral 2004). But, these arguments have a weak scientific basis. We would discuss them in the subsequent paragraphs.

As regards the first point, the impact of zero marginal cost is not in 'creating incentive to wastewater', but in 'creating disincentive to prevent wastage'. These two concepts are distinctly different for public irrigation systems as control of water delivery devices is not in the hands of the farmers. One exception is the situation where Water Users' Associations (WUAs) function, which considers water use to the point about 'disincentive'. The reason for disincentive is that the direct cost or the opportunity cost of taking measures to prevent wastage would be more than the benefits that can be derived from it in the form of reduction in yield losses. In certain other situations, in the absence of proper control structures in the tertiary systems, water delivery is not regulated. Given that farmers are unsure of getting the next release in time, they apply water excessively and irrespective of the field capacity of the soil. This is common in paddy, which is widely grown in canal commands. So, the impact of a price increase would be the creation of a strong economic incentive to reduce wastage, equal to the irrigation charges they have to pay for the wasted water.

The second point is about linking irrigation charges and demand for water. Merely raising water tariff without improving the quality and reliability of irrigation will not only make little economic sense but also would find few takers. As returns from irrigated crops are more elastic to quality of irrigation than its price (Kumar and Singh 2001), poor quality of irrigation increases farmers' resistance to pay for the irrigation services they receive. Therefore, the 'water diverted' by farmers in their fields does not reflect the actual demand for water in a true economic sense, so long as they do not pay for it. In other words, the impact of tariff changes on irrigation water demand can be analyzed only when the water use is monitored and farmers are made to pay for the water on volumetric basis.

It also means that if positive marginal prices are followed by improved quality, the actual demand for irrigation water might actually increase, though efficiency would improve. To what extent it would increase depends on the availability of land and alternative crops that give a higher return per unit of land. This increase in demand is due to the tendency of farmers to increase the volume of water used to maintain or raise the net income (Kumar and Singh 2001). Hence, water rationing is important to affect demand regulations in most situations (Perry 2001a). The challenge lies in understanding the science of WP, particularly WP response to irrigation and actual consumptive use of water, and managing irrigation water deliveries accordingly. In the case of well irrigation, it is important for farmers to understand this linkage, whereas the official agencies have to ensure that power supply is available for critical waterings.

As regards the third point, often farmers do not make correct judgments about the level of irrigation dosage that corresponds to zero marginal returns. This has been found in the case of well owners, who are not confronted with the positive marginal cost of pumping, resulting in lowering the yield with incremental irrigation (Kumar 2005). Price reforms only make farmers more conscious about the negative economic consequences of giving an overdose of irrigation water.

Opportunities for Improving Farm-level and Regional-level Water Productivity

We have seen that there are clear trade offs between options to enhance physical productivity of water and WP in economic terms at the field level itself. We would see that there is a trade off between maximizing WP at the field level and that at the farm level, though farm level water productivity is dependent on the processes that govern WP at the individual fields. We would also see that the options available to maximize WP in a region, which often is the concern of water policymakers, are far fewer in the case of individual farms. The water policymaker looks for approaches that would not only enhance the economic returns, but also increase the social welfare. Many of the decisions relating to public investment in irrigation systems in countries like India are driven by larger societal concerns such as producing more food, employment generation and poverty alleviation. Often, policymakers are more driven by social and political considerations than purely economic considerations (Perry 2001a). We would elaborate on these issues in the subsequent paragraphs.

From the analysis presented in the previous section, it is evident that the scope for improving field level WP is extremely limited given the social, economic, institutional and policy environment in India. Limitations are greater when we want to use it as a driver for changing water demand. Therefore, WP enhancement should focus on crops that are inherently more water efficient in economic terms and also have a high return per unit of land. As Molden (per. com) notes, “increasing WP is not often relevant to farmers. If it is important to the society, then society should figure out ways to align everyone’s incentives.”

It is established that many fruit crops have higher WP (Rs/m^3) than the conventional cereals such as wheat and paddy in arid areas. For instance, pomegranate grown in north Gujarat gives a net return of nearly Rs.40,000 per acre (i.e., USD900/acre) of land against Rs.8,000 per acre (i.e., USD180/acre) in case of wheat. The WP is approximately Rs.100/m^3 for pomegranate (Kumar 2007) against Rs.4.46/m^3 for wheat in the same region. Also, there are crops such as potato, cumin, cotton and castor which are more water efficient than rice and wheat, which can be grown in Punjab (see Table 3). With greater reliability, and control over water delivery, farmers using well irrigation would allocate more water for growing water-efficient crops. Perhaps, farmers have already started shifting to high-valued cash crops.

But, there are limits to the number of farmers who can take up such crops due to the volatile nature of the market for most of these crops, its perishable nature, and the high risk involved in producing the crop. For instance, cumin grown in north Gujarat is a very low water consuming crop, with a high return per ha. But, crop failure due to disease is very common in cumin. In case of vegetables, that are fast perishable, markets are often very volatile, and price varies across and within seasons. The problem of price fluctuation is also applicable to cotton grown in western Punjab, which has high WP. Also, the investments for crops are also very high, demanding a high degree of risk-taking.

But, farmers organize their entire farm, rather than the field, to maximize the net economic returns (Ruthenberg 1980). The extent to which farmers can allocate water to economically efficient crops would perhaps be limited by the need to manage fodder for animals. It may also get limited by the poor market support for orchard crops. Many farmers in Punjab and other semi-arid parts of India manage crops and dairy farming together. But, even globally, there is a dearth of research, which analyzes WP in composite farming systems that really take into

Table 3. Applied water productivity in selected crops in north Gujarat, western Punjab and eastern Uttar Pradesh (UP).

Sr. No.	Name of the Crop	Net Water Productivity of Crop (Rs/m^3) of Applied Water in		
		Western Punjab	Eastern UP	North Gujarat
1	Kharif Paddy	7.75	4.78	-
2	Fodder Bajra	2.93	4.78	-
3	Kharif Cotton	40.40	-	-
4	Kharif Castor	-	-	8.09
5	Brinjal	-	-	-
6	Wheat	8.05	9.11	4.46
7	Fodder Jowar	6.32		-
8	Mustard	-	-	4.73
9	Winter Gram	24.48	-	-
10	Jowar	-	-	4.01
11	Cumin	-	-	19.84
12	Summer Bajra	-	-	2.85

Source: Based on Kumar et al. (forthcoming) for western Punjab and eastern UP; and Kumar (2005) for north Gujarat. In the case of north Gujarat crops, the mean values of water productivity figures for different categories of farmers were taken

account water depleted in biomass production. Literature on water use efficiency and WP in dairy farming is also extremely limited. In regions for which they are available, the conditions are extremely different to those in countries like India. Studies from northern Victoria and southern New South Wales analyzed water use efficiency in dairy farms that are irrigated (Armstrong et al. 2000). In these regions dairy farming is not integrated with crop production. Green fodder produced in irrigated grasslands is used to feed the cattle by dairy farmers in Australia and United States, unlike sub-Saharan Africa and developing countries in South Asia.

Recent analyses from western Punjab seem to suggest that the overall net WP in Rupee terms becomes enhanced when the byproducts of cereal crops are used for dairy production (see Table 4).

The reduced area under cereal, crops such as paddy and wheat, would translate into a reduction in the availability of fodder. Farmers may have to grow special crops that give green fodder, and in that case, they might in turn be increasing the intensity of water use in Punjab. In a similar semi-arid situation in north Gujarat, it was found that dairy production, which used

Table 4. Water productivity in crops and dairy production.

Sr. No.	Name of Crop/ Farming	Water Productivity (Rs/m^3)
1	Paddy	7.75
2	Wheat	8.05
3	Milk Production	13.06

Source: Kumar et al. forthcoming (derived from Table 11) irrigated alfalfa, was highly water-inefficient, both physically and economically (Singh 2004; Kumar 2007). Otherwise, farmers may have to procure dry fodder from outside, which would involve more labor. Hence, there could be a 'trade off' between maximizing crop WP and farm level WP, but there is not much literature about economic productivity in dairy farming, especially with cereals and dairying, to understand this trade off.

At the regional level, enhancing WP through either a shift to water efficient crops (like orchards and vegetables) or to a crop-dairy based farming system might face several constraints from a socioeconomic point of view. Food security is an important consideration when one thinks about options to enhance WP. Punjab produces surplus wheat and rice, which are exported to other parts of the country to meet their cereal requirements (Amarasinghe et al. 2004). Nearly 22.1 % of India's wheat production and 10.8 % of its rice production comes from Punjab (source: Ministry of Agriculture, Government of India).

The labor absorption capacity of irrigated agriculture and market price of fruits are other considerations. Paddy is labor intensive. As per some recent estimates by Kumar and Singh (2008), 2.614 million ha of irrigated paddy in Punjab (as per 2005 estimates) needs 159 million labor days during the peak kharif season. This is based on the primary data, which shows that a hectare of paddy creates Rs. 5,000 worth of farm labor in Punjab. This is exclusive of the machinery employed in ploughing and harvesting. With a wage rate of Rs.80 per day, the number of labor days per ha of irrigated paddy is estimated to be 61 (source: primary data from Punjab). This labor requirement is met by migrant laborers from Bihar. Replacing paddy with cash crops would result in a reduction in farm employment opportunities.

On the other hand, the lack of availability of labor and fodder would constrain intensive dairy farming to maximize WP at the regional level, though some farmers might be able to adopt the system. This contradicting situation with regard to labor is caused by the fact that most of the labor used for paddy is obtained from seasonal migrants, who go back to their homes after the main field operations in paddy, whereas dairying would require daily labor, and constant care and attention for the animals. As regards fruits, its large-scale production might lead to a price crash in the market, and farmers losing revenue unless sufficient processing mechanisms are established. Hence, the number of farmers who can adopt such crops is extremely limited.

In the context of a developing country, the potential for poverty reduction or impact of irrigation on food security are more important than the return per unit of water. Food security and poverty reduction are in-built goals for large-scale subsidies in irrigation (Gulati 2002), which enable poor farmers to intensify cropping. Therefore, WP in irrigation too needs to be looked at from that perspective, and not merely on a 'crop per drop' basis. One can argue that with more reliable irrigation, farmers could also produce more food or generate more employment, and with that, achieve higher physical and economic productivity along with meeting social objectives. But, the heavy subsidies in irrigation reduce the ability of the agencies to improve its quality through regular investments.

Perhaps this welfare-oriented policy of keeping irrigation charges low needs a re-look. With extensive well irrigation in India and with the poor paying heavy charges for pump renting or well water to irrigate their crops, the policies to subsidize canal irrigation may not bring about the desired equity and welfare outcomes. In fact, a large portion of the subsidies in canal irrigation goes to large farmers, due to the following of a crop-area based pricing system (Kumar and Singh 2001). These farmers also have access to well irrigation in the command area.

Another fact that supports the above argument is that often the unreliable canal water supplies force farmers to adopt only paddy, and not domestic food security concerns. The stable and high procurement prices offered by the Food Corporation of India for cereals such as rice and wheat allow farmers to stick to this cropping system. But there are major macro-economic imperatives of trying to meet these social objectives (Gulati 2002). The intensive paddy cultivation in Punjab is associated with the intensive use of electricity for pumping groundwater even in canal commands during the summer. Irrigating one ha of winter wheat requires 74 Kwhr to 295 Kwhr of electricity, which costs Rs.300 to Rs.1,175 to the economy (source: field data). The region is already facing a power crisis, which adversely affects the reliability of power supplied to the farm sector. Enhancing productivity of pumped groundwater also means enhancing energy productivity and reducing revenue losses to the government in terms of power subsidies.

If farmers are able to secure a higher net return from every unit of water applied or depleted in well irrigation, this could be a major starting point for irrigation bureaucracies to start charging higher rates for irrigation along with improving the quality, adequacy, reliability and control of water. Following the norms of rationing in water allocation would be crucial in achieving higher WP. Perhaps, what would be required would be higher prices for food crops or special incentives for farmers who grow such crops so as to reflect their social benefit, while reducing the irrigation subsidies heavily. So, the net result would be a compromise between socioeconomic productivity and productivity enhancement in monetary terms, with a positive impact on the water resource system.

Summary of Findings

The data from limited research presented in this paper shows that technically there is great scope for enhancing agricultural water productivity without crop shifts. This can be achieved through improved quality and reliability of irrigation and changing water allocation to crops, and not so much through water harvesting and supplementary irrigation, and MI technologies. But to create economic incentives for large-scale adoption of such measures among farmers as well as irrigation bureaucracy, the electricity/water pricing policies have to change towards pro rata pricing of electricity and volumetric pricing of canal water. Unless we resort to pricing instruments, the avenues for significantly enhancing WP can be generated only through crop shifts, and in certain cases through a crop-dairying mix. But such measures have trade-offs such as increase in farming risk, regional food insecurity and unemployment.

Research to explore potential improvements in physical productivity of water (kg/ET) in crops without due consideration to income returns per unit of water will not be relevant for Indian farmers under the current electricity and water pricing policies in agriculture, and institutional regimes governing water use. The reason is it does not link WP improvement to raising the aggregate of farm income. In countries like India, major determinants for analyzing improvements in basin level WP due to WH and supplementary irrigation should use: i) incremental economic returns from enhanced crop yield; and ii) opportunity costs of water harvesting at the basin scale. Analysis of basin level impacts of efficient irrigation technologies on basin WP and water saving should involve and consider CF as a determinant of WP rather than that of evapotranspiration.

Research on the potential impact of improved quality and reliability of irrigation water and changing water allocation on WP is relevant for India, as it gives due consideration to maximizing farmers' income, while reducing the total water depleted. Nevertheless, their overall potential in improving WP and more so in reducing water demand in agriculture is open to question, unless policies and institutions are aligned to make society's interests and farmers' interests match. This is because farmers can expand the area under irrigation also in areas where land is still left unirrigated due to the shortage of water. For the composite farming systems that are characteristic of countries like India, WP research should focus on optimizing water allocation over the entire farm to maximize returns, through changes in the crop mix and crop-livestock compositions. But due consideration should be given to the risk taking ability of the farmer, investment capabilities etc.

In countries like India, research on measures to enhance regional level WP should integrate socioeconomic considerations such as food production, employment generation along with wealth generated per unit of water used in irrigation. But, often farmers' choice of food crops like paddy is not by design, but by default. Meeting food production needs or other social objectives cannot be an excuse for poor productivity. Given these goals, regional WP scenarios can examine the scope for improving WP through increment in the productivity of crops such as wheat and paddy with reliability and control regimes in irrigation, along with other measures.

Conclusions

There are limited numbers of options available to significantly enhance agricultural WP in countries like India, given the larger objective of addressing food security, poverty alleviation, and employment generation concerns in rural areas. The options are: improving quality and reliability of water; and, changing water allocation. In the short term, focus should be on technical interventions to enhance the WP of existing crops that are based on improving reliability, adequacy, and water allocation for reducing non-beneficial consumptive use, and non-beneficial nonreusable portions of water supplies. The inherent advantages of well irrigation systems need to be built while designing surface irrigation systems and designing water allocation norms. But, in most cases, they could regulate water demand only if water allocation is rationed volumetrically. Hence, in the medium and long term, electricity and water pricing policies have to be made more efficient so as to expand the opportunities for WP improvements without increasing farming risks, domestic and regional food insecurity and unemployment. Only this can link WP improvements to raising the income of the farming households.

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Opportunities and Constraints to Improving Water Productivity in India

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Introduction

To assess the current levels of water productivity in agriculture and the scope for improving the same would require a clear understanding of the various considerations that should be involved in assessing it. Needless to say, assessing water productivity in agriculture merely on the basis of the crop output or income returns per unit of water diverted or depleted would lead to inappropriate policy decisions for improving agricultural water management. The reason is that improvement in field level water productivity alone is not the objective in agricultural productivity growth (Loomis and Connor 1996; Kumar and van Dam 2008). Policymakers and farmers alike are equally concerned about the changes that occur in the farming system as a result of such changes, and their impact on the resilience of the farming system and implications for farmers' risk taking ability. The policymakers are also concerned about how the water is used at the level of the irrigation system and the river basin, and what economic outputs it generates (Chakravorty and Umetsu 2002; Molle and Turral 2004). Other concerns are: what happens to food security, the regional agricultural economy and the environment as a consequence of the interventions made at the field level to raise crop water productivity.

Analyzing water productivity in agriculture involves complex considerations arising out of the intricate nature of the water supply and water use system, the farming systems, the regional, social and economic environment in which the farming system is embedded and the physical environment with which the farming system interacts. As we are aware, there are major differences in the hydrological, economic and environmental considerations involved in analyzing water productivity in accordance with the differences in: 1) scale of analysis of 'irrigation efficiency' from field to farm to irrigation system to the river basin (Keller et al. 1996; Seckler et al. 2003); 2) objectives of water productivity analysis; 3) parameters used in analysis, i.e., in physical or economic values or a combination of physical and economic values (Kijne et al. 2003); 4) environmental considerations; 5) food security considerations; and 6) concerns in regional economic growth (Kumar and van Dam 2008). Surely, there are trade-offs between addressing these concerns in agricultural productivity growth and enhancing water productivity.

In this paper, first we discuss these complex considerations that should be involved in assessing water productivity in agriculture. Concurrently, we also discuss how the incorporation of such considerations change the way we evaluate water productivity or even limit or expand our options to improve water productivity in agriculture. In other words, we examine the trade-off between raising water productivity in agriculture and improving farming system resilience, food security, employment generation in rural areas and regional economic growth. Based on an understanding of these considerations and trade-offs, we identify the opportunities and constraints for improving water productivity in both rain-fed and irrigated agriculture in India. Finally, a quick assessment of the scale of enhancement of water productivity in India is made on the basis of the range of physical, technical, socioeconomic and institutional and policy factors influencing the future potential for its improvement.

Different Considerations in Analyzing Water Productivity

Scale Considerations

The 'scale considerations' are important in the comparative analysis of water productivity (Molden et al. 2003; Kumar and van Dam, 2008; Palanisami et al. 2008). This is more so when the type of irrigation changes, for instance from canal irrigation to tank irrigation to well irrigation. This is owing to the fact that generally, 'irrigation dosage' is higher than the crop water requirement (ET-effective precipitation) for water-abundant surface schemes as compared to groundwater based schemes; and the frequency of irrigation is definitely lower than in well irrigation. This leads to a high dosage per watering, resulting in runoff, percolation and non beneficial evaporation in canal irrigation. But many of the 'losses' at the farm level such as percolation and field runoff appear as 'gains' at the system and basin level as these outflows get captured at the lower side of the system or basin. This is particularly important in Punjab as irrigated paddy with continuous ponding of water is extensive there. As 'depleted water' rather than 'diverted water' will have to be considered while estimating water productivity functions, the unit of analysis has to move away from 'field' to the 'system' and then to the basin.

But, an alternate view is provided by Palanisami et al. (2008) who argues that since the irrigation bureaucracy is concerned with maximizing the returns per unit of water delivered from the reservoir, system level water productivity for surface irrigation schemes should be assessed in relation to the total amount of water delivered from the reservoir. They used the total water released from the system for assessing water productivity at the system level and showed that water productivity declined when moved from 'field' to 'system'. However, this study did not take into account either the production or the income generated from the use of return flows pumped by well irrigators inside the command of the irrigation system.

In the transit from system to basin, there could also be opportunities for improving the water productivity of a given crop due to climatic advantages. The appropriate selection of agro-climate plays an important role in enhancing productivity levels, without any significant changes in water control regimes (Abdulleev and Molden 2004; Zwart and Bastiaanssen 2004). Besides this, Chakravorty and Umetsu (2002) showed that with optimal allocation of water over the entire basin, increase in economic benefits is much more under modern methods than the traditional methods of irrigation. Their conclusions were on the basis of simulation studies of economic benefits from basin-wide optimization of surface water allocation for irrigation for traditional and modern methods of irrigation after incorporating the use of return flows from canals through wells. ,. Hence, considerations for enhancing regional or basin level productivity would be different from that for maximizing the field level productivity (Cai and Rosegrant 2004; Gichuki 2004; Molle et al. 2004). Furthermore, at the basin level, several competing water using sectors exist. So, opportunities for improving water productivity exist through: 1) transfer of water to alternative uses in any part of the basin; 2) growing certain crops in regions where ET demands are low involving inter-regional water allocation; and, 3) allocating water to economically efficient crops within the same region.

These are very important factors. For instance, an analysis of water productivity in the Narmada River basin showed that WP of wheat in both physical and economic terms varies significantly from the upper catchment area of the Narmada to its lower catchments. This difference was mainly due to the variations in climatic conditions, which change the denominator of water productivity, i.e., the consumed water (Kumar and Singh 2006). Even within the small geographical unit of the Bist Doab area, the variations in agro-climatic conditions between central Punjab and sub-mountainous area in the foothills of the Shivalik induced by difference in rainfall regime, temperature, humidity and soils are wide (source: Hira and Khera 2000). But, paddy and wheat are the dominant crops in the entire region.

As farmers' water allocation decisions are for the farm as a whole rather than for the field (Loomis and Connor 1996: pp 393-394), scale considerations are extremely important in analyzing water productivity even at the individual farmer level. Within a farm, there are several crops cultivated during the same season. Often, crops and dairying are practiced in an integrated manner. There are very few pockets in India where farmers practice mono-cropping. Even in the most intensively irrigated Punjab, which is criticized for its paddy-wheat system, sugarcane, fodder crops and low water-consuming mustard are all grown in the same farm by farmers who simultaneously cultivate paddy and wheat. The determinants of water productivity would change as one moves from the field to the farm i.e., the determinants would be the net return from the farm against the total amount of water diverted or depleted at the farm level. For estimating the denominator, the amount of water imported into the farm or exported from the farm should also be factored, rather than the total water applied by the farmer in the field or used for feeding cattle. Hence, judging the productivity of water usage in agriculture by looking at a few major crops would be misleading. As seen in the case of Punjab, water productivity in dairy farming, which heavily depends on residues from paddy and wheat, was much higher than that of water productivity in individual crops (Kumar and van Dam 2008).

Now, to what extent the irrigation water applied to the system is a 'loss' from the system would be determined by whether groundwater is shallow, or saline or deep or whether waterlogging conditions exist. The plains of central and north eastern Punjab are underlain by alluvial aquifers. At present, farmers pump water mostly from the upper phreatic aquifer, which is shallow. Hence, in such areas, a major share of the return flows from irrigated fields, especially paddy fields, and are likely to end up in the groundwater system. But, such areas are very rare in India. The exceptions to this are perhaps many. In areas with deep water table conditions, having a deep vadoze zone, not all the water, which moves vertically down, would end up with the groundwater system. Most of the semi-arid and arid regions of India, where water scarcity is an issue, have deep groundwater table conditions, be it in the alluvial North Gujarat, arid areas of Rajasthan or in the southern peninsular. In such areas, soil conditions do not favor the fast percolation of water. Thus the gain in applied water productivity would result in a gain in real water productivity in most situations.

In areas with saline groundwater, like in western Punjab, the return flow cannot be treated as a 'gain' but a 'loss' from the system, as groundwater quality is far below the standards required for irrigation. Hence, geo-hydrological environment is an important physical consideration in analyzing water productivity functions.

Parametric Considerations

'Parameter considerations' are extremely important in comparing water productivity. Choosing the right parameter for assessing water productivity is important while judging which irrigation source yields higher water productivity. Following are the reasons: a) it has been found that farmers in well command areas prefer crops that are less water consuming (ET) as compared to those grown in fields irrigated by canals, hence capturing the economic value of outputs is extremely important, in addition to looking at the irrigation efficiencies and physical productivities; b) both the public cost of production and supply of water (water storage, diversion and irrigation) and private cost of water supply (irrigation) can vary widely between gravity irrigation and well irrigation, and hence need to be understood by looking at economic efficiency; c) the opportunity cost of using water could vary significantly between surface water and groundwater, as the scope/ opportunity for transferring water to alternative (higher-valued) uses could be different. Hence, economic returns from a unit of water depleted in surface irrigation against the opportunity costs of depleting that water in groundwater irrigation should be considered in a comparative analysis of water productivity between wells and canals or between wells and tanks.

Parameter consideration is also important when comparing water productivity in agriculture across two regions which have differential water endowments. It is quite well known that the incremental return from every unit of water diverted would be much higher in a water-scarce region as compared to a water-rich region even when the farmers are not confronted with the opportunity cost of using the water. This is because of the difference in the balance between arable land and water availability between the two regions (Kumar et al. 2008a).[1] But, it is also well understood that the opportunity cost of using a unit volume of water would also be different. So if the full opportunity cost of diverting the water for agriculture at the societal level is considered, does the gain in marginal productivity that is observed in water-scarce regions, offset the differential opportunity cost of using water to give a better return for every Rupee spent on water? Hence, taking the crop yield or crop returns from a unit volume of water diverted or depleted won't be sufficient under such circumstances.

Objective of Analysis of Water Productivity

In crop productivity analysis, one important issue is knowing which 'crop' and which 'drop' is referred to (Molden et al. 2003; Bastiaanssen et al. 2003). The 'objective of analysis' would change with the underlying concerns. In the recent decades, the need to consider the 'depleted fraction' as a determinant of water productivity, rather than the total water applied to the crop, has gained acceptance. Scholars are increasingly concerned about the amount of water depleted

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[1] In the naturally water-poor region, the land that can be brought under cultivation is extensive, a factor that contributes to the high demand for irrigation water, whereas in the water-rich region, there is a shortage of arable land, which keeps the demand for irrigation water low.

in the system rather than the total water applied to the field (see for instance, Allen et al. 1998; Molden et al. 2003; Molle and Turral 2004). Such views ignore productivity losses due to deep percolation in inefficient irrigation systems. This is because water resources management alone becomes the primary concern for those who are engaged in the research on water productivity. Whereas as Palanisami et al. (2008) notes, irrigation bureaucracy would be primarily concerned with what is generated out of the water delivered from the scheme and, therefore, they would assess the system level water productivity in relation to the total water supplied.

The underlying concern should depend on which resource used in crop production, apart from water, is scarce; i.e., whether it is energy or other inputs, and which resource is critical from a management point of view. In a region, where energy is scarce, allowing excessive return flows in the form of recharge and runoff would not be justifiable, as it would require precious energy to pump it for reuse. This would have major economic imperatives and the objective should also be to maximize the return from every unit of energy used. Especially in a country like India, where 65 % of the irrigation occurs through pumping, analysis of irrigation efficiency cannot ignore energy efficiency. Therefore, the estimates in the 'opportunity cost' of using water should include the cost of production of the energy required for lifting the 'return flow fraction' and the incremental value of the benefits accrued from alternative uses of the depleted fraction. This means that in regions which are facing a power crisis, the concern should also be in reducing the deep percolation of irrigation water besides reducing the depletion fraction, and raising the yield and net returns.

Food Security Considerations

A nation, although facing water shortages, may decide to produce food within its own territory instead of resorting to imports due to social and political reasons. In such situations, economic efficiency of production may not be of great relevance, as the country may strategically decide to subsidize the farmers to procure systems that provide control over irrigation water delivery and thereby improve the physical productivity of water. Instead, the opportunity cost of importing food may be taken into consideration and treated as an additional benefit while estimating the incremental value of crop output for estimating the 'economic productivity' function. These considerations seem to be extremely important for India if one goes by the recent analysis by Shah and Kumar (2008). The analysis shows that the social benefits due to incremental food production (42 million tonnes) through investment in large reservoir projects, since Independence, in terms of lowering food prices, was to the tune of Rs. 4,290 crore annually. If food security impacts of certain crops are integrated with the analysis of crop water productivity, then the arguments of low water productivity in gravity irrigated paddy-wheat systems would be irrelevant. In fact, paddy and wheat are the staple food of many Indians, and self-sufficiency of these two crops is very important despite their low water productivity. But, as pointed out in 'Paper 2' of this book, food security itself cannot be an excuse for low productivity. Many canal irrigation systems, in fact, suffer from poor quality and reliability of water supplies, which impacts on water productivity adversely.

The attempt should, therefore, be in improving the productivity of water through improving the quality and reliability of water supplies in the canal irrigation systems that mimic well irrigation. This assumes greater significance when one considers the fact that most of the irrigated cereals such as paddy, wheat, bajra and jowar have much lower water productivity in simple economic terms than oil seeds, vegetables and fruits (Kumar and van Dam 2008).

Environmental Considerations

In a region where rising groundwater tables and increasing salinity is a concern, one of the objectives of water productivity improvement should be to reduce the return flows, along with reducing the depletion fraction. This is because the opportunity cost of leaving the water underground through return flow is high, owing to the environmental damage it causes. Intuitively, there could be significant differences in return flows between canal irrigation and well irrigation. Therefore, comparative analysis of water productivity between well irrigated crops and canal irrigated crops in such regions should involve opportunity cost considerations rather than the volume of water diverted or depleted. Here, the opportunity cost of using the diverted water should include the cost of providing subsurface drainage for the recharge fraction of the return flow, and the benefits that can be derived from alternative use of the depletion fraction part of the total water diverted. Here again, since there is a spatial mismatch between the demand for water and supplies available through return flow, ideally, the incremental value of the benefits that can be accrued from alternative uses of the 'total applied water' should be considered in estimating the opportunity cost rather than the 'water depleted'. This is because the return flows won't find much beneficial use in the area.

Let us examine how environmental cost and benefit considerations can alter water productivity assessments. For that, we consider the canal command areas. Many canal command areas in India have shallow groundwater due to seepage from canals and irrigation return flows from the fields. Examples are Sutlej Canal commands in Punjab and Haryana; Ukai-Kakrapar command in south Gujarat; Mula command in Maharashtra and Krishna and Nagarjunasagar commands in Andhra Pradesh. In certain cases, the return flow from canal irrigation is a boon as it provides the additional recharge to sustain groundwater irrigation. Whereas in certain other cases, it is a bane as it causes waterlogging conditions. Whether it becomes a boon or a bane depends on the original groundwater table conditions in the area before the introduction of canal water, and the balance in groundwater use.

Now, well irrigation exists in canal command areas, in lieu of the poor reliability of canal water supplies. In cases like central Punjab, the area irrigated by tubewells has surpassed the area irrigated by canals over the years. In certain cases, well irrigation is sustained by return flows from canals as in the case of central Punjab and Mula command in Maharashtra. Whereas in certain other cases, well irrigation prevents conditions of waterlogging, which can occur due to excessive seepage and return flows from canals as seen in Ukai-Kakrapar and Mahi commands in south and central Gujarat, respectively. In the first case, while analyzing the productivity impacts of canal irrigation, the environmental benefit of providing the critical recharge that protects the groundwater environment can be considered in the numerator of water productivity. In the second case, while analyzing the water productivity impact of well irrigation, positive environmental effects of preventing waterlogging conditions should be considered in assessing the net returns, while there may not be any opportunity costs associated with its use for irrigation.

Regional Economic Considerations

A standard approach to improve water productivity in agriculture and to reduce the stress on groundwater would be to replace low water-efficient crops by those which are highly water-efficient (Kumar 2007). An approach as such will have differential impacts on the economy in different regions.

For example, in North Gujarat, there is a severe problem of groundwater depletion, resulting primarily due to dairy production. Although Diary production accounts for a major portion of its rural economy (Kumar 2007), it is highly water-intensive due to green fodder production (Singh 2004; Kumar 2007). The introduction of highly water-efficient crops, such as orchards and cash crops like cumin in such an area would result in the replacement of dairying. But, this would result in lower production of milk, which provides a stable income and a regular cash flow for the farmers. Hence, it is a difficult proposition from the farmer's perspective. Moreover, dairy cooperatives have already invested heavily for processing and marketing of milk and milk products. Thus there are strong political economic considerations that go against measures of protecting groundwater ecology in North Gujarat. Also, although it is easier for the farmers to maneuver inputs such as dry fodder and green fodder to the farm, it is difficult for the region as a whole to import large fodder requirement for dairying. Thus, at the regional level, replacement of dairying by cash crops and orchards would have significant impact on the region's milk production, which not only sustains its rural economy, but also produces a surplus for export to other deficit regions.

In order to analyze the opportunities and constraints for improving regional water productivity in agriculture and to reduce the stress on groundwater, farm economy in four sub-regional (talukas) of Banaskantha District in North Gujarat were simulated using linear programming. The results from two different optimization models (minimization and maximization models), for the four talukas were more or less similar. Results from the Vadgam Taluka of Banaskantha District of North Gujarat showed that the volume of groundwater used for agriculture can be reduced to an extent of 49.5 % through the introduction of cumin or lemon. This would not affect the initial level of net farm income or compromise the food security needs of the region's population. However, while doing this, the milk production would undergo a sharp decline. This is because milk production is relatively more water intensive, and any effort to cut down groundwater use would result in reducing milk production and substituting it with crops that are highly water productive.

With the introduction of water-saving technologies (WSTs) for field crops including alfalfa, the extent of reduction that was possible in groundwater use was higher (60.1 %), with lower extent of reduction in milk production. The net farm output, however, would not be adversely affected. Further analysis showed that using WSTs, the groundwater use could be brought down by 17.5 %, if milk production in the region has to be maintained at the previous level. The extent of reduction possible in groundwater use decreases with the degree of unwillingness to compromise milk production. This means that, the amount of leverage available for enhancing regional water productivity and cutting down groundwater use for farming becomes limited if the income from dairy production as a percentage of the total farm income is to remain high.

A great deal of risk taking by farmers is involved in the adoption of orchard crops and drip irrigation systems. In the former, it is due to the need for finding markets and in the latter, it is the capital intensive nature of the system. Hence, the small and marginal farmers show great reluctance to adopting such systems. Thus, there is a trade-off between enhancing the water productivity of the farming system through crop and technology selection and reducing farming risks.

In certain other regions, the greatest constraints in enhancing agricultural water productivity are: a) arable land availability; b) market for farm produce; and c) labor absorption. In regions like Punjab, which are intensively cropped, improving the productivity of water use in agriculture through crop shifts could be at the cost of the regional agricultural economy itself. The reason for this is that many of the highly water-efficient crops have low land productivity, and higher water productivity could be essentially due to the low water requirement of the crops. Shift towards such crops would lead to an overall decline in the economic outputs from farming, since farmers won't have the opportunity to expand the area under irrigation to sustain the income from farming.

It is established that many fruit crops have both higher water productivity and land productivity than conventional cereals such as wheat and paddy in arid areas (Kumar and van Dam 2008). Also, there are crops such as potato, tomatoes, cumin, cotton and groundnut which are more water efficient than rice and wheat, which can be grown in Punjab. Farmers from this region have already started shifting to high-valued cash crops in a moderate way. But, the number of farmers who can take up such crops is limited due to the volatile nature of the market for most of these crops, their perishable nature and also the high risk involved in their cultivation.[2] Furthermore, given the high investments required for the crops, there arises a need for greater risk-taking ability. But, the extent to which farmers can allocate water to economically efficient crops would perhaps be limited by the need to manage fodder for dairying, which is more water efficient than the conventional paddy-wheat system. It may also be limited by poor market support for orchard crops.

The foregoing discussion shows that the potential trade-off exists between maximizing field level water productivity through crop shifts and maximizing water productivity at the level of the farming system. The possibility exists for simultaneously enhancing both field and farm level water productivity through the introduction of high-valued crops such as vegetables and fruits—if those crops have water productivity values higher than those in dairy production. Otherwise, if the water productivity of the newly introduced crop is not higher than that of dairying, but higher than that of the cereals, fodder will have to be imported to practice dairying. However, in both cases, the risk involved in farming might increase. The reason is the volatile nature of vegetable prices and the high probability of a drastic price increase or fodder scarcity, in the event of a drought (Singh and Kumar Paper 5, this book).

Now, at the regional level, attempts to adopt water efficient crops or crop-dairy based farming to enhance agricultural water productivity might face several constraints from a socioeconomic point of view. National food security is an important consideration when one thinks about crop choices. Punjab produces surplus wheat and rice and supplies them to many other parts of India, which are food-deficit, including eastern India (Amarasinghe et al. 2005; Kumar et al. 2007). Twenty percent of the country's wheat production and 10 % of its rice production comes from Punjab, and they contribute 57 % and 34 %, respectively, to the central pool of grains for public distribution (Kumar et al. 2007).

Labor absorption capacity of irrigated agriculture and market prices of fruits are other equally important considerations at the regional level. Paddy is labor intensive and a large portion of the migrant laborers from Bihar work in the paddy fields of Punjab. As per our

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[2] The markets for fast perishing vegetables are often very volatile, and price varies across and within seasons. The problem of price fluctuation is also applicable to cotton grown in western Punjab, which has high water productivity.

estimates, 2.614 million ha of irrigated paddy in Punjab (as per 2005 estimates) creates 159 million labor days[3] during the peak kharif season. The total percentage of farm labor contributed by migrant laborers during the peak season was reported to be 35 % as per the Economic Survey of Punjab 1999-00 The total number of labor days contributed by migrant laborers to paddy fields in Punjab was estimated to be 55.75 million (Singh and Kumar Paper 5, this book).

Replacing paddy by cash crops would mean a reduction in farm employment opportunities. On the other hand, the lack of availability of labor and fodder would be constraints for intensive dairy farming to maximize farming system water productivity at the regional level, though some farmers might be able to adopt the system. Large-scale production of fruits might lead to price crashes on the market, resulting in farmers losing revenue unless sufficient processing mechanisms are established. Hence, the number of farmers who can adopt such crops is extremely limited.

Summary on Trade Offs

Enhancing field level water productivity in many situations would involve trade-offs in the form of reducing return flows to groundwater that is crucial for increasing the productivity of water at the basin level through well irrigation. The trade-off can also be in the form of increasing farming risk due to a shift towards risky cash crops with volatile markets. But, as Palanisami et al. (2008) notes, the irrigation bureaucracy may not consider this as a trade-off when it comes to surface water, as they are preoccupied with the task of maximizing their revenue and, as such, are interested in maximizing the area directly irrigated by the canals and other surface water sources.

At the regional level, enhancing agricultural water productivity would be constrained by existing farming system and the consideration of food security, employment generation and regional economic stability. Nevertheless, WP improvement might come from a shift from cereals and high labor absorbing crops to capital-intensive and risky cash crops that decrease the farming system's vulnerability to market risks. Whereas integrating environmental considerations in water productivity improvement measures would justify the investments for the same in waterlogged areas.

Choosing the right parameter for assessing water productivity is important when judging which irrigation source yields higher water productivity. While comparing water productivity between two sources of irrigation, with the differential opportunity costs of using the resource, one must assess the economic productivity of water. The objective of water productivity analysis should determine the major determinants for assessing it. In regions where energy is scarce, the cost of pumping back the return flows from irrigation should be added to the opportunity cost of the depleted water while comparing water productivity between cases of differential return flows.

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[3] This is based on the primary data which show that a hectare of paddy creates Rs. 5,000 worth of farm labor in Punjab. This is exclusive of the machinery employed in ploughing and harvesting. With a labor charge at the rate of Rs. 80 per day, the number of labor days per ha of irrigated paddy is estimated to be 61 (source: primary data from Punjab).

Opportunities for Improving Regional Water Productivity in India

Discussion on Hot Spots for Water Productivity Improvements

Opportunities for Water Productivity Improvement in Rain-fed Agriculture: With the rapid expansion in well irrigation, India does not have purely rain-fed areas now in the strict sense of the definition. But, there are rain-fed crops in many regions, including central and peninsular India. This is because some crops are always irrigated in every region, though some farmers might be growing those crops under rain-fed conditions there. Often, farmers who do not have irrigation facilities resort to the purchase of water to provide critical supplementary irrigation. An example is cotton growing in Maharashtra and Madhya Pradesh. However, the situation with regard to the extent of irrigation keeps varying with rainfall variability. In a high rainfall year, a certain crop might give high yields without irrigation, whereas in a low rainfall or drought year, securing optimum yield would not be possible without supplementary irrigation.

Most of India's 'so called' rain-fed areas are in central India and the peninsular region. Of these, the central Indian belt deserves special mention. This region is dominated by tribes, who are the first or second generation agriculturists (Phansalkar and Verma 2005). In spite of abundant natural resources, by and large, the population in this region is not able to improve their farming considerably, owing to their peculiar cultural and socioeconomic conditions. Instead, they mostly practice subsistence farming and grow most crops under rain-fed conditions. Development of water resources for irrigation is poor in these regions; the use of modern farming practices including the use of fertilizers and pesticides and crop technologies is extremely low. The result is that the productivity is low for cereals, and the total factor of productivity growth is also very poor. The other food grain crops grown extensively in this region have a low productivity (Amarasinghe and Sharma, Paper 2 of this book). Hence, this region is characterized by agricultural backwardness.

Amarasinghe and Sharma (Paper 2, this book) show that there are 208 districts where the average consumptive use of water for food grain production is low (below 300 mm), due to larger areas being under rain-fed pulses such as green gram, black gram and horse gram. These crops have very low grain yields, resulting in low WP. The study which used an analysis of the district level aggregate for data on crop outputs and average consumptive use of water (CWU), also shows that supplementary irrigation can boost both yield and WP significantly (Amarasinghe and Sharma, Paper 2 of this book). This boost would be through farmers shifting from short duration food grain crops to long duration irrigated crops, such as wheat in winter and from rain-fed paddy to irrigated paddy.

This tribal region forms the upper catchment of important river basins in India such as Mahanadi, Godavari, Tapi, Mahi, Narmada, Krishna, Sabarmati and Banas, spread over the states of Orissa, Madhya Pradesh, Chattisgarh, Maharashtra, Gujarat and Rajasthan. These regions form the rich catchments responsible for a major portion of the basin yields, which are appropriated for down-stream uses (GOI 1999; Kumar et al. 2006). The flows in some of these basins are already exploited to their full potential for irrigation and other uses through storage and diversion systems, and further exploitation in the upstream areas would be at the cost of downstream uses—Mahi, Krishna, Sabarmati and Banas (Kumar et al. 2006).

Large-scale irrigation projects are coming up in the Narmada River basin, where 29 large, 125 medium and around 3,000 minor schemes are planned to be built. Work on some of them is already completed. The percentage cropped area currently irrigated in the basin is very small. The rain-fed crops occupy large areas in the basin (Kumar et al. 2004). The rain-fed crops account for a major part of the basin's water economy. Many of these crops are those which need supplementary irrigation to realize their yield potential. Kumar and Singh (2006) show that the irrigated crops and crops receiving supplementary irrigation in the basin have much higher water productivity as compared to rain-fed ones in both physical and economic terms. Once built, these irrigation schemes will be able to bring the rain-fed areas in the basin under irrigated production, and thereby raise crop water productivity. The productivity impacts would be visible in crops such as irrigated cotton, pulses such as gram, black gram and green gram; and cereals such as paddy and wheat.

But, there are still a few basins, where small-scale water resources development is possible without causing negative effects on the downstream. They are Tapi, Mahanadi and a few small river basins (Karjan and Damanganga) in South Gujarat. Since the geo-hydrological environment is not very congenial for storage of the harnessed water underground due to hard rock strata, water can be stored in small-scale reservoirs such as anicuts, check dams, ponds and tanks. But, the water resources being developed should be put to beneficial use immediately after harvest. The reason is that the potential evaporation rates are high in most parts of these regions even during the monsoon (Kumar et al. 2006) and as a result the stored water can be lost to evaporation. This means that the supplementary irrigation of kharif crops is the best option for use of this harvested water.

In peninsular India, rain-fed crops are still grown in many parts due to: a) low and erratic rainfall b) poor surface water availability; and c) groundwater endowment. This region is mostly underlain by hard rock formations. The problem of natural water scarcity in the basins is compounded by demand for water far exceeding the renewable water resources. The basins are also closed or are on the verge of closure (Kumar et al. 2008b). Small water harvesting interventions in the upper catchments of such basins would only help basin-wide redistribution of water, with negative implications for basin water use efficiency (Kumar et al. 2006). The only exception to this is the Godavari River basin, which is water-surplus. Augmentation in water resources would be possible and the same water could be used to bring rain-fed crops under irrigation to boost crop yields. In any case, large-scale water resource development projects based on river lifting are coming up in this region and would help expand irrigated agriculture, and thereby boost crop water productivity.

In addition to the low water (ET) consuming short duration rain-fed (food) crops or water stressed rain-fed (food) crops, there are rain-fed crops, which require a moderate use of water (300-425 mm) in 117 districts of India. These crops, which are essentially long duration fine cereals, are concentrated in eastern India and central India. Amarasinghe and Sharma (Paper 2 of this book), show the yield gap of these food grain crops is very high. Use of better crop technologies, and better inputs could also result in significant improvement in water productivity through yield enhancement, which would be the effect of nutrients and proportion of the ET being used for transpiration.

Opportunities for Water Productivity Improvement in Irrigated Agriculture: Kumar et al. (2008c) demonstrated on the basis of a detailed study of three river basins in India (Narmada, Sabarmati, parts of Indus and Ganges) that there are five major avenues for improving water productivity in irrigation crops, with other scholars sharing similar views. They are: 1) water delivery control; 2) improving quality and reliability of irrigation water supplies (Palanisami et al. 2008;

Kumar et al. Paper 3, this book); 3) optimizing the use of fertilizers; 4) use of micro- irrigation systems (Palanisami et al. 2008; Sikka, Paper 4, this book); and, 5) growing certain crops in regions where they secure high water productivity. Studies in the Narmada Basin show that great opportunities for improving water productivity (in economic terms) exist through control over water delivery. This can mean allocating less water in many instances with a resultant reduction in yield but rise in WP to allocating more water in certain instances with a resultant increase in both yield and WP (Kumar and van Dam 2008). Amarasinghe and Sharma (Paper 2, this book) show results that conform to the fact that water productivity in irrigated crops could be enhanced significantly through deficit irrigation, a key strategy in water delivery control in 251 districts. These are districts which already show very high yield per unit of land, and receive intensive irrigation.

Different types of micro-irrigation systems that are amenable to different crops and cropping systems are available. While some are only technically feasible and economically viable for row crops and orchards, some are feasible and economically viable for field crops also. They can improve crop water productivity by reducing the non-beneficial evaporation or non-recoverable deep percolation in the field, resulting in total depletion or consumed fraction (CF).[4] Or they can increase the proportion of the beneficial fraction of the applied water that leads to improved crop yield. Nevertheless, in both cases water productivity is improved without any reduction in yield (for details, Please see Kumar et al. 2008c; Palanisami et al. 2008). There are other conservation technologies such as zero-tillage and bed planting, which can improve water productivity in wheat (Sikka, Paper 4, this book).

The determinants of physical productivity of water such as yield and evapotranspiration are influenced by climatic factors—with solar radiation and temperature affecting yield, solar radiation, temperature, wind speed and humidity affecting ET (Agarwal et al. 1995; Loomis and Connor 1996) and agronomic factors—with crop variety affecting the potential yield and ET requirement (Hussain et al. 2003). Since yield affects the gross returns, the climate would have implications for water productivity in economic terms as well. Hence, certain crops give higher water productivity in both physical and economic terms by virtue of the climate under which they are grown without any additional inputs of nutrients and improved crop technology (Loomis and Connor 1996: pp 398). Studies in the Narmada Basin show major differences in water productivity of wheat and irrigated paddy across nine agro-climatic subregions (Kumar and Singh 2006).

In the case of wheat, the physical productivity of applied water for grain production during the normal year was estimated to be highest for the northern region of Chhattisgarh in Mandla District (1.80 kg/m^3). Although falls in the traditional wheat-growing belt, WP was lowest for Jabalpur in Central Narmada Valley (0.47 kg/m^3). This is mainly due to the major difference in irrigation water applied, which is 127 mm against 640 mm for Jabalpur. This is a significant difference, with the highest being 250 % more than the lowest. The difference in irrigation can be attributed to the difference in climate between Jabalpur (dry semi-humid) and Mandla (moist sub-humid), which changes the crop water requirement. Higher biomass output per unit volume of water (physical productivity) should also result in higher economic output,

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[4] Please see Allen et al. (1998) for various definitions.

especially when the difference is mainly due to climatic factors, which changes the ET requirements, unless the factors which determine the cost of inputs significantly differ. In this case here, it was found that the net economic return per cubic meter of water was highest for the same region for which physical productivity was higher (Rs. 4.09/m^3). But the same was lowest for Narsinghpur (Rs. 0. 86/m^3), which had the second lowest physical productivity.

As regards paddy, there are only two regions which irrigate paddy. The physical productivity for grain during the normal year was estimated to be higher for the northern region of Chhattisgarh in Mandla District (2.13 kg/m^3), whereas it was only 1.62 kg/m^3 in Jabalpur District of Central Narmada Valley. Likewise, the combined physical and economic efficiency of water use was found to be higher for Chhattisgarh (Rs. 3.59/m^3) against Rs. 1.43/m^3 for Jabalpur in Central Narmada Valley. Climatic advantage exists in many major basins such as Indus, Ganges, Cauvery, Sabarmati and Narmada) with lower aridity, higher rainfall and higher humidity experienced in the upper catchments (based on Kumar et al. 2006; and Kumar et al. 2008b). For instance, within the paddy-wheat growing area of Punjab, the climate varies from hot semi-arid to hot and sub-humid. This advantage can be tapped to allocate more land for water-intensive crops in localities where ET requirement is less and there is greater sunshine.

Another major opportunity for water productivity improvement comes from crop shifts. In every region, the agro-climate permits the growing of several different crops in the same season, and our analysis shows that there are major variations in water productivity in economic terms across crops (Kumar and Singh 2006; Kumar et al. 2008c). Several of the cash crops, such as castor, cotton, fennel, cumin and ground nut, and vegetables, such as potato, are found to have a higher water productivity than the cereals grown in the same region (Kumar and Singh 2006; Kumar et al. 2008a; Kumar and van Dam 2008). But, if we consider the food security benefits of growing cereals, the opportunity available for WP improvement through a crop shift may not be significant in major food producing areas. In such areas, the opportunities for shifting from less water-efficient nonfood crops to water-efficient cash crops and fruits should be explored. Semi-arid pockets such as North Gujarat, Saurashtra, central Madhya Pradesh, western Rajasthan, northern Karnataka, parts of Tamil Nadu and western parts of AP are ideal for such crop shifts to improve crop water productivity and reduce the stress on groundwater. These, however, are not major food producing areas.

There are many irrigated districts in eastern India which are dominated by food crops. The yield of food crops such as wheat and paddy is very low in these districts, and yield gaps are high (Kumar et al. 2008d), and also the total factor growth is very low (Evenson et al. 1999). Amarasinghe and Sharma (Paper 2, this book) show that there are 202 districts in the country which fall under the category of medium consumptive water use of irrigated crops (300-425 mm), but with high yield gaps. Improved agronomic inputs (high yielding varieties and better use of fertilizers and pesticides) can significantly raise the yields. This will have a positive impact on water productivity, though water productivity is not a concern for farmers in this water-abundant region of India. While there are districts in central India, where better use of fertilizers would help enhance crop yields, these areas also require optimum dosage of irrigation to achieve this (Kumar et al. 2008c).

As regards improvements in quality and reliability of irrigation, it is more relevant for canal irrigated areas, and areas receiving tank irrigation (Palanisami et al. 2008). The area irrigated by canals is high in Punjab, Haryana, Uttar Pradesh, Bihar, Maharashtra, Tamil Nadu and Andhra Pradesh. Some of these areas have good native groundwater and farmers could supplement canal water with well water. Such areas include central and north eastern Punjab, Uttar Pradesh and Bihar. Whereas in parts of Maharashtra, Tamil Nadu and Andhra Pradesh, the hard-rock aquifers get replenished due to return flows from canal irrigated fields and seepage from canals. This is already extensively practiced in Punjab, Maharashtra and South Gujarat.

Sikka (Paper 4, this book) shows that introducing horticulture, fish and prawn farming, and rearing ducks through secondary reservoirs and raised bed-cum trench could enhance water productivity in economic terms in the seasonally waterlogged areas of Bihar, under the rice-wheat system in order of magnitude. Also, in seasonally waterlogged paddy areas, introduction of horticulture-fish production in raised bed cum trench was found to be economically viable. Sikka's work also shows that many rice farms in eastern India are multiple use systems with significant values being added by trees, fisheries and dairying, and assessing their water productivity in relation to the returns from paddy production against the total water delivered would lead to a significant underestimation of water productivity of such agricultural systems. Nevertheless, the water accounting procedure adopted in the study did not take into account the increased water demand induced by trees or the actual amount of water directly used by trees from the subsurface strata. Hence, it is quite likely to have resulted in the overestimation of incremental water productivity obtained under the farming system.

In some other areas, where groundwater is scarce or is of poor quality; quality and reliability of irrigation water supplies could be improved through creation of intermediate storage systems like the one found in Bikaner District of Rajasthan. But, one pre-requisite for this is the availability of land area for cultivation and farmers' ability to spare land for construction of such storage systems. Area irrigated by tanks is high in the South Indian states of Andhra Pradesh and Tamil Nadu.

Constraints to Improving Water Productivity in Agriculture

Constraints to Rain-fed Agriculture

Socioeconomic and Financial Constraints: Rockström et al. (2002) show that supplementary irrigation through water harvesting will have a remarkable effect on the productivity of water (expressed in kg/ET) for crops such as sorghum and maize. However, the research did not evaluate the incremental economic returns due to supplementary irrigation against the incremental costs of water harvesting. It also does not quantify the real hydrological opportunities available for water harvesting at the farm level and its reliability. The work by Scott and Silva-Ochoa (2001) in the Lerma-Chapala Basin in Mexico showed a higher gross value product from crop production in areas with better allocation of water from water harvesting irrigation systems. But, the figures of surplus value product which takes into account the cost of irrigation are not available in their analysis. In arid and semi-arid regions, the hydrological and economic opportunities of water harvesting are often over-played. A recent work in India has shown that the cost of water harvesting systems would be enormous, and reliability of supplies from it very poor in arid and semi-arid regions of India, which are characterized by low mean annual rainfalls, very few rainy days, high inter-annual variability in rainfall and rainy days, and high potential evaporation leading to a much higher variability in runoff between good rainfall years and poor rainfall years (Kumar et al. 2006; Kumar et al. 2008b).

Given that incremental returns due to yield benefits may not exceed the cost of the system, as indicated by the comparison between the unit cost of water harvesting and recharging schemes and the net returns from a unit volume of water obtained in irrigated crops (Kumar et al. 2008b), small and marginal farmers will not have the incentive to go for water harvesting. But, even if the benefits due to supplementary irrigation from water harvesting exceed the costs, it will not result in basin-level gain in WP in economic terms in closed basins. The exception is when the incremental returns are disproportionately higher than the increase in ET. This is because, in a closed basin, increase in beneficial ET at the place of water harvesting will eventually reduce the beneficial ET down stream, causing income losses there. Also, as Kumar and van Dam (2008) point out, incremental net benefit considerations can drive water harvesting at the basin scale only if there is no opportunity cost in harvesting.

In open basins, water harvesting and recharge schemes could be attempted to improve water productivity of crops, but, the following are prerequisites: 1) the harvested water is put to high-valued use, making the system economically viable from the point of view of economic costs and the incremental benefits; 2) the system is used to produce crops which provide very high social returns, especially in improving the regional food security and employment. In closed basins, it would be difficult to justify investments in water harvesting and recharge schemes from an economic perspective, unless the incremental returns due to the upstream interventions are far higher than the opportunity costs of downstream economic losses and mechanisms are in place to compensate for these losses.

Unfortunately, the regions, which are endowed with water-rich basins, have a very high concentration of tribal population. They are used to grow subsistence crops like paddy and maize which have low economic returns and water productivity (Rs/m^3). Hence, most of the preconditions for achieving water productivity gain through supplementary irrigation are not likely to be satisfied. This poses socioeconomic constraints.

Investments for water harvesting and groundwater recharge schemes that can help improve water productivity in rain-fed farming systems are very high in terms of cost per cubic meter of water (see Table 1), even if they are economically viable or are able to generate high social returns. The poor tribes are least likely to mobilize these resources. Hence, there are financial constraints too. Large-scale government financing of water harvesting and groundwater recharge systems would, therefore, be required.

Table 1. Estimated unit cost of artificial recharge structures built under pilot scheme of CGWB.

Sr. No	Type of Recharge Structure (Life in years)	Expected Active Life of the System	Estimated Recharge Benefit (TCM)	Capital Cost of the Structure (in Lakh Rs.)	Cost of the Structure per m^3 of water (Rs/m^3)	Annualized Cost* (Rs/m^3)
1	Percolation Tank	10	2.0-225.0	1.55-71.00	20.0-193.0	2.00-19.30
2	Check Dam	5	1.0-2100.0	1.50-1050.0	73.0-290.0	14.60-58.0
3	Recharge Trench/Shaft/	3	1.0-1550.0	1.00-15.00	2.50-80.0	0.83-26.33
4	Subsurface Dyke	5	2.0-11.5	7.30-17.70	158-455.0	31.60-91.00

Source: Kumar et al. (2008b) based on GOI 2007, Table 7: pp14

Note: *Estimated by dividing the capital cost by the life of the system

Social Constraints: Water productivity improvement in rain-fed farming really matters for socioeconomically backward regions, and is actually important for those who do not have the wherewithal to invest in conventional irrigation systems. There are many ways productivity (both land and water) in rain-fed farming can be raised. Some of them are: a) use of drought resistant varieties; b) use of irrigation combined with high yielding varieties and fertilizers and pesticides; and c) use of highly water-efficient and high-valued dry land crops. Sikka (Paper 4, this book) shows that the introduction of fishery in a water harvesting pond meant for supplementary irrigation of paddy could enhance farm returns and water productivity significantly in rain-fed paddy areas. But, the poor people in these backward regions lack the knowledge and capacity to adopt the technologies needed, including the appropriate fish variety, the feed etc. Poor knowledge about modern agricultural practices, compounded by poor information about markets and lack of marketing skills, prevent them from investing in high productivity farming systems.

Constraints to Improving Basin-level Water Productivity in Irrigated Agriculture

Physical Constraints

We have seen that within the same basin, great opportunities for improving water productivity of a given crop exist if we can earmark certain regions for certain crops, on the basis of the climate. But, along with water productivity, total agricultural output is also a concern for the agricultural and water sector policymakers. The regions which have favorable climate for growing a crop with less water should also have sufficient land that can be allocated to the crop in question. From that angle, constraints seem to be emerging. Many water-intensive crops like paddy and wheat are today grown in regions which have large arable land, but having hot and arid climates. Shifting these crops to areas with a more moderate climate within the same basin or elsewhere can result in a sharp decline in production, as these areas have much lower arable land, as shown by a recent analysis provided in Kumar et al. (2006) for five major river basins of India, viz., Narmada, Indus, Krishna, Sabarmati, and Cauvery. Also, crop yields might be lower in those regions due to ecological reasons such as lower temperature and solar radiation which actually can reduce ET, but have negative implications for potential yield (Loomis and Connor 1996: pp 398). An example is growing paddy and wheat in Bihar instead of Punjab and Haryana.

Institutional Constraints

For the same type of system, water productivity for the same crop can change at the field scale (Singh et al. 2006:pp272) according to water application and fertilizer use regimes. Changing water allocation strategies at the field level can help enhance WP. For this it is important to know the marginal productivity with respect to changing the dose of irrigation water and nutrients. Farmers' water allocation decisions are governed by institutional regimes determining the use of water. Let us examine the constraints in achieving marginal productivity gains from an institutional perspective.

For a given crop, the irrigation dosage and the crop water requirement (beneficial use plus beneficial nonconsumptive use) corresponding to the maximum yield may not correspond to the maximum water productivity (Rs/m^3)—(Molden et al. 2003). The WP (k/m^3) would start leveling off and decline sharply before the yield starts leveling off (Molden et al. 2003). Ideally, WP in terms of net return from a crop per cubic meter of water (Rs/m^3) should start leveling off or decline even before physical productivity of water (kg/m^3) starts showing that trend. When water is scarce, there is a need to optimize water allocation to maximize water productivity (Rs/m^3) by changing the dosage of irrigation. But, this may be at the cost of reduced yield and net return per unit of land, depending on which segment of the yield and WP response curves the current level of irrigation corresponds to.

Recent analysis with data on applied water, yield and irrigation WP for select crops in the Narmada River basin in India showed that in many cases, trends in the productivity of irrigation water in response to irrigation did not coincide with the trends in crop yields in response to irrigation. In this case, limiting irrigation dosage might give higher net return per unit of water. But, farmers may not be interested in that unless it gives higher return from the land. The reason is that they are not confronted with an opportunity cost in using water, due to the absence of well-defined rights in use of surface and groundwater. Though at the societal level, the resource might be scarce, at the individual level, the resource-rich farmers might enjoy unrestricted access to it. This is the major institutional constraint in improving water productivity.

Hence, if the return from the land does not improve, the strategy of restricting water allocation can work only under three situations: 1) the amount of water farmers can access is really limited either by the natural environment, e.g., limited groundwater reserves; 2) there is a high marginal cost of using water due to the high prices for water or electricity used for pumping water that it is much closer to the WP values at the highest levels of irrigation; and, 3) water supply is rationed. In all these situations, the farmers should have extra land for using the water saved. Under rationing of supply, farmers would anyway be using water for growing economically efficient crops (Kumar 2005; Singh and Kumar 2008). But, the issue being addressed here is for a particular crop that how far WP of this crop can be enhanced to a level that the best managed farms achieves at present. In all these three situations described above, the WP improvements would lead to farmers diverting the saved water for irrigating more crops to sustain or enhance their farm income. The reason is that the amount of water being handled by farmers is too small that they need to use the same quantum of water as previously since the WP differences are just marginal.

But, situations like those described above, where farmers are confronted with the opportunity cost of using water, are not very common. Even in the hard-rock areas with poor groundwater environment, farmers are frantically drilling bore holes to tap water from deeper strata, thereby overcoming the constraints imposed by physical shortage. While restriction in power supply is being tried by governments to limit farmers' access to groundwater, in reality this is leading to greater power theft and more inequity in the distribution of benefits from a subsidized power supply. There are very few locations in India where canal water supply is heavily rationed in volumetric terms. Hence, the only way to create an incentive among farmers, who are inefficiently using irrigation water, to initiate measures to improve WP is by enforcing volumetric water rights or entitlements with pro rata tariff for canal water (Kumar and Singh

2001) and groundwater (Kumar 2005) or energy quotas combined with high power tariff in case of groundwater (Zekri 2008).

Market Constraints

Major gains in water productivity (economic terms) are possible through crop shifts towards more water-efficient ones such as low water consuming fruits and vegetables that give high income returns (Kumar and Singh 2006; Kumar and van Dam 2008) at the level of individual farms, though the possibility of doing that is determined by the climate. For instance, pomegranate fruit produced in North Gujarat has an applied water productivity of Rs. 39/m^3 of water under tube- well irrigation under normal market conditions. But, highly volatile market conditions and poor marketing infrastructure induces major constraints to improving water productivity and reducing the stress on water resources.

Although the demand for fruits and vegetables is increasing steadily in India with increasing income, due to the seasonal nature of these crops, local markets often get flooded with the produce during those seasons, leading to a price crash. In order to avoid this, the supply of this produce to the market needs to be regulated so that a significant portion of it reaches the market when the production is low. Another intervention is to take the produce to distant markets where the climate is not favorable for producing such crops, but provision of cold storages and instant freezing technologies are needed for this. Earmarking of large areas under traditional crops to such high-valued crops can add to the woes of the farmers. The reason being that most of these crops (many fruits and vegetables) perish quickly, and hence need to be brought to the markets immediately after the harvest.[5] These areas require good road infrastructure for transport. Whereas, for other crops such as onions and potatoes, infrastructure for post harvest treatment of the produce would be required. However, many regions in India, where productivity levels are very low also lack good infrastructure facilities including electricity.

Policy Constraints

Inefficient pricing of electricity in the farm sector, characterized by heavy subsidies and charging on the basis of connected land, is a major policy constraint to improving water productivity in agriculture (Kumar 2005; Kumar et al. 2008c; Zekri 2008). Nearly 60 % of India’s irrigated area gets its water supplies from wells (Kumar 2007). Well-irrigated fields are more amenable to technologies and practices for improving crop water productivity, because of the greater control that farmers wield over irrigation water application. One of the most important agricultural technologies to improve water productivity in crops is micro-irrigation, while in terms of practices, control over water allocation (Kumar et al. 2008c) and improving the quality and reliability of water (Trivedi and Singh 2008) can help improve water productivity. Heavy subsidies and flat rate pricing of electricity in agriculture leaves no incentive among farmers to secure higher water productivity through improved water allocation and micro-irrigation systems, as they do not lead to improved returns from a unit of land (Kumar and van Dam 2008; Kumar et al. 2008c).

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[5] Storing such produce in cold storage etc., will not be economically viable.

Several of the recent studies from Uttar Pradesh, Bihar and Gujarat highlight the positive impact of introducing pro rata pricing of electricity in agriculture on field level water productivity (Kumar 2005 for Gujarat) and water productivity of the entire farming system (Kumar et al. 2008e; Singh and Kumar 2008 for all the three states). Kumar et al. (2008) showed that the price of electricity could be raised to such a level that the marginal cost of water for the farmer who owns an electric well becomes equal to that of the farmer who owns a diesel well, provided good quality power supply is assured (Kumar et al. 2008e). But, the proposals for metering electricity in the farm sector and introducing pro rata pricing get rejected on flimsy grounds. One of them is that farmers are rural vote banks, and that raising power tariff is highly unpopular as it would make farming less attractive. It is to an extent true that merely raising the power tariff would only lead to increasing the cost of irrigation in areas where power supply is of very poor quality. This is because farmers would be discouraged from choosing a cropping system that is water-efficient, but often high risk, due to the fear of supply interruptions and crop damage. Another argument against metering and pro rata pricing is the transaction cost of metering large number of wells in remote rural areas.

But, one important factor that is missed in the entire discussion on raising power tariffs is the improved quality of power supply that is possible under a metered tariff. Under flat rate tariff, it is important to regulate the power supply to reduce the negative effects on welfare, such as excessive pumping, misuse of groundwater and electricity, inequity in distribution of subsidy benefits and greater revenue losses to the electricity board. This affects the quality of irrigation, but this is not necessary under pro rata pricing. Improving the quality of power supply would change the energy-irrigation nexus (Kumar 2005). Singh and Kumar (2008) showed that pro rata pricing with high energy tariff leads to better equity in access to groundwater, and apart from securing higher water productivity, the farmers got higher returns per unit of land and used lesser amounts of groundwater. All these are achieved through the careful selection of crops, and farming systems that use lesser amounts of water, but give higher returns per unit of land, and use all inputs including water more efficiently.

But, these were rather excuses used by officials and other functionaries of electricity departments to cover up the revenue losses due to poor operational efficiencies, resulting from transmission losses and distribution losses, which included thefts. Also, unmetered connections attract more bribes, as detecting power theft is much more difficult under a flat rate system. A recent survey in North Gujarat showed that farmers are resorting to under-reporting of connected load, after the implementation of the much-publicized *Jyotigram Yojna*[6] in villages, which made direct power theft from feeder line difficult. Obviously, detecting thefts like this would require field visits by the technicians, and checking the connected load. Hence, the flat rate system is patronized by a section of the engineering staff of electricity boards. As a result, the state's governments find it rather convenient to continue with such policies. Such degenerative policies act as a major constraint to improving water productivity in agriculture. But, it is important to recognize the fact that resistance to metering is not from the farming lobby, but from the bureaucracy itself.

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[6] It involved separation of feeder line for agriculture and domestic power supply.

Technological Constraints

We have seen in an earlier paper that one of the most effective ways of improving water productivity is by ensuring greater control over water delivery. In the case of well irrigation, farmers can exercise good control over water delivery, provided electricity supply is reliable. Diesel well owners were found to be securing very high water productivity in economic terms in spite of incurring high marginal costs for irrigation water due to high diesel prices, in comparison to electric pump owners who incur very low cost for using energy and water (Kumar et al. 2008e; Singh and Kumar 2008). The control over irrigation water is one major factor which enables them to allocate water optimally. There are very few states in India where power supply to agriculture is reliable and adequate. Gujarat is one among them. Many states are facing power crises, and agriculture has been at the receiving end, which has to be satisfied with irregular, erratic, untimely and short duration supply of electricity (GOI 2002). Under such a supply regime, controlled and quality irrigation is not at all possible. Erratic and short duration power supply also induces constraints to farmers adopting precision irrigation systems like drips and sprinklers which are energy-intensive in certain cases.

One disincentive for well irrigators for improving crop water productivity is lack of opportunity cost of using groundwater and electricity in many states. One way of inducing this opportunity cost is by restricting the energy use by farmers. Technologies exist for controlling energy consumption by farmers. The pre-paid electronic meters, which are operated through scratch cards and work on satellite and internet technology, are ideal for remote areas to control groundwater use online (Zekri 2008). As Zekri (2008) notes, such technologies are particularly important when there are large numbers of agro wells, and the transaction cost of visiting wells and taking meter readings is likely to be very high. Hence, they are ideal for the Indian condition. But, such technologies are still not accepted in India. Resistance to introducing such technologies due to vested interests within the state electricity departments is also notable.

In the case of canal irrigation, devices which provide control over water delivery to the lowest delivery regions in the irrigation system are lacking in most of the old gravity irrigation systems. This is a major hindrance for farmers to exercise sufficient control over water application. Most irrigation systems are designed using old design concepts with very few control structures. While intermediate storage systems like the ‘diggie’ in Rajasthan can help farmers leverage control over water application, in many instances they are not feasible due to problems in land availability. In the case of Bikaner in Rajasthan, Amarasinghe et al. (2008) showed that ‘diggies’ in Rajasthan are economically viable when the landholding is larger than four acres.

Scale of Agricultural Water Productivity Improvements and its Potential Implications for India’s Future Water Scenario

Assessing the scale of water productivity improvement in agriculture is a complex task given the range of physical (climate, geo-hydrology and soils) conditions, the socioeconomic conditions (cropping patterns, overall economic condition of farmers, and the infrastructure conditions, and the institutional and policy environment that determine and influence the water productivity levels that are achieved at present, and the water productivity improvements that are possible in the future. The physical environment, which is more or less static, would influence the future enhancement possible in crop water productivity, irrespective of the intervention chosen.

Water Productivity Improvement through Micro-irrigation

In the case of micro- irrigation systems, not only the physical environment but the water supply systems and the socioeconomic environment also would determine the ultimate scale of adoption of MI systems. After Kumar et al. (2008f), water productivity improvements through the use of micro-irrigation systems are likely to be significant for crops planted in rows and orchards. Furthermore, it would be higher in regions/basins where climate is semi-arid to arid, soils are light and sandy and where the groundwater table is deep. This is because in the case of row-planted crops, the evaporation component of the consumptive water use by crop (ET) is quite large, especially under arid conditions (Kumar et al. 2008f). Again, the area under row-planted crops is very small in the sub-humid and humid areas and water abundant areas. Regions with sub-humid to humid climatic conditions, heavy soils, and with shallow groundwater tables, improvements in water productivity through MI systems are likely to be negligible. But, so far as their adoption goes, that is likely to occur in well-irrigated areas, and not so much in canal irrigated areas owing to the need for special storage systems for water.

Peninsular India and western India have substantial area under crops that are conducive to micro-irrigation technologies; north and central India has very little area under such crops with the exception of Uttar Pradesh. Western part of Mahanadi is another area that would be conducive to WSTs. Use of micro-irrigation system can significantly reduce crop water demand per unit area of cultivated land in semi-arid and arid area, with deep groundwater table conditions or with saline aquifers. But, in these areas, farmers would use the saved water to expand the area under irrigation and thereby maximize their aggregate returns in the presence of sufficient uncultivated land. As a result, the aggregate demand for water may not change. Exceptions would be those where intensity of irrigation is already high like in central Punjab and Haryana.

Kumar et al. (2008f) estimated the total area that can be brought under micro-irrigation systems in India, where their adoption would actually lead to water productivity improvement as much as 5.9 million hectares. The reduction in agricultural water requirement that was estimated to be possible through this was 44 billion cubic meters (BCM)—(Kumar et al. 2008).

All these measures will be for well-irrigated areas. Still, a large part of the irrigated area (23.606 M ha in 1999-2000 in India, source: Ministry of Agriculture and Cooperation, GOI), which is from surface sources, would be left untouched. The first step to bring these areas under MI systems is to either change the delivery practices or to increase the economic incentives. The water delivery systems need to be designed in such a way that farmers can directly connect the source to their distribution systems. The irrigation schedules need to be reworked in such a way that the duration between two turns becomes much shorter than the present 2-3 weeks. In the most ideal situation, the supply has to be perennial. This can happen in the most advanced stage of irrigation systems design, and would take time. Over and above, it can be thought about only in the case of new schemes.[7]

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[7] One of the reasons why the farmers in Israel adopt micro-irrigation systems at such a large-scale (with 95 % of the irrigated crops are under drip systems) is that the surface water is delivered in their fields under pressure through pipes.

Economic incentives for MI adoption in canal commands can be improved by increasing the price of irrigation water. High prices for irrigation water would affect cost saving as a result of applied water saving. Alternatively, the cost of building the intermediate storage systems can be reduced through the proper design of subsidies. The justification for subsidizing the systems is that the private benefit-costs ratio would not be very attractive with very high capital costs and the additional infrastructure that is required, whereas the social benefits accrued from saving the scarce water resources would be high when compared against the social costs. In the command area of Indira Gandhi Canal Project, most of the farmers are using intermediary storage tanks, which are locally known as 'diggies'. The farmers are using electric pumps for lifting this water and they irrigate crops whenever required. The government has started providing subsidies for the construction of 'diggies'. Many farmers are using sprinklers to irrigate their crops from tank water. But, such responses have come from the farmers due to the drastic cuts introduced by the irrigation department in the allocation of water.

Apart from saving the cost of water, the differential economic returns farmers get under lift irrigation over canal irrigation (IRMA/UNICEF 2001; Kumar and Singh 2001) and the differential return in drip irrigated crops would be the strongest incentive for farmers to go for intermediate storage systems. The differential returns could be due to better control over water delivery possible with lift irrigation (IRMA/UNICEF 2001) or due to the increased ability to grow cash crops such as cotton, banana, and fruits and vegetables in the command areas. In canal commands where water becomes a limiting factor for expanding irrigated area, area expansion would be the strongest economic incentive for adopting intermediate storage systems and MI systems. This is what drives farmers in IGNP towards 'diggies' and mini sprinklers (Amarasinghe et al. 2008). With this, the actual area that could be brought under MI systems would be larger than the estimates we have provided for the potential area under MI system.

The canal command areas in the semi-arid parts of Andhra Pradesh, Maharashtra, North Gujarat, Rajasthan, Madhya Pradesh, northern Karnataka and Tamil Nadu are ideal for this. The sub-humid and humid areas should be excluded from being considered for MI interventions in canal commands, as the benefits of yield and water saving are likely to be insignificant. We estimate the total canal irrigated area to be around 9.54 million ha from the six basins namely, Godavari, Krishna, Cauvery, Pennar, Narmada, Sabarmati; and the west flowing rivers of Saurashtra and Kachchh; the east flowing rivers between Mahanadi and Pennar; and the east flowing rivers south of Pennar. But, of this, a small fraction could actually be brought under drip systems, as the crops amenable to this system (such as cotton, castor, fruits and vegetables) would cover a small area in these surface irrigation commands. A slightly larger area could be covered under sprinklers as crops amenable to this technology such as potato, groundnut, fodder crops, wheat, bajra, jowar and mustard would cover a much larger area.

Water Control and Improving Quality and Reliability of Irrigation

Empirical studies, which compared crops receiving well irrigation with their counterparts under canal irrigation, show that the differential quality and reliability of water has a positive impact on applied (Kumar et al. Paper 3, this book) and depleted water productivity (Palanisami et al. 2008) of crops. The measures for water productivity enhancement through improvement in quality and reliability of irrigation water and 'water delivery control' are more relevant for field crops and surface irrigation systems. This is due to the poor quality and reliability of irrigation, and the poor control over water delivery that they generally experience due to heavy discharge rates, low frequency of water delivery and absence of proper schedules followed in irrigation.

The gains in water productivity per applied water through 'water control' are similar to the gains in water productivity per depleted water, only in semi-arid and arid regions. In these regions the depth to groundwater table is large[8] and non-beneficial evaporation from fallow land is high. All the applied water or a significant portion of the applied water would be depleted in these regions. Hence, there would be basin level productivity gains through control over water delivery.[9] But, for farmers to agree to water control measures, they must have extra land to bring under irrigation. This is because the net return per unit area might decline due to water control measures. Hence, at the aggregate level, there would be no reduction in the demand for water.

The basins that are conducive to measures for water productivity improvement through water control are: 1) all east-flowing rivers of peninsular India; 2) rivers north of Tapi in Gujarat and Rajasthan, Mahanadi, and in some parts of the Indus Basin covering south-western Punjab; and 3) west- flowing rivers of South India. This is because these basins are falling under semi-arid and arid climatic conditions, and have moderately deep to deep groundwater levels. These basins have very large areas which are unirrigated due to limited availability of groundwater and canal water. Hence, farmers would have an incentive to improve water productivity as in the process they would be able to maximize the aggregate returns.

There are some regions in India where water productivity is not a consideration for individual farmers. But, the economy here would benefit a lot by reducing the amount of water depleted and the energy used in growing crops. Such areas include parts of Indus in central Punjab, Haryana and UP, which are groundwater irrigated. In such areas, water productivity improvement measures should help raise income returns from every unit of land irrigated. Hence, the only option to enhance the available water productivity is water delivery control, which can be used in situations where excessive irrigation leads to yield losses. According to Amarasinghe and Sharma (Paper 2 of this book), there are 251 districts in which a calculated reduction in irrigation water supplies could result in improved water productivity. In some of them, measures for WP improvement could result in enhanced crop production as farmers would be able to expand the irrigated area using the water saved. Whereas in some others, yield gain due to controlled irrigation can occur in situations if excessive irrigation is leading to yield losses.

In two of the earlier papers, we have seen that improvement in quality and reliability of irrigation water would have a positive impact on water productivity in both physical and economic terms (Palanisami et al. 2008; Kumar et al. Paper 3, this book). In Punjab, Haryana, the canal irrigated areas of Maharashtra, Andhra Pradesh and Tamil Nadu, improving quality and reliability of canal water supplies, in addition to reducing non-beneficial depletion and improving water productivity, would lead to a greater yield for cereal crops. Hence, the irrigation department should have an incentive to go for improving both the quality and reliability of irrigation water, and 'water control' as well. Such measures are even applicable for water-rich regions like Bihar where excessive irrigation resulting from poor quality and reliability leads to yield losses as reported by Meinzen-Dick (1997).

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[8] Deep groundwater table and aridity means that the return flows from applied water are not significant; and evaporation of residual soil moisture from fallow is very high.

[9] In other regions—sub-humid and humid regions with shallow groundwater, the basin level water productivity gain would be very much lower.

Water Productivity Improvement through MUS

Going by Sikka (Paper 4, this book), water productivity in rice-wheat systems could be significantly enhanced through the introduction of fisheries, agro-forestry and duckery. This involves the use of a secondary reservoir fed by canal seepage with replenishment from tubewell for fish-duck production; and, fish trench cum raised bed for fish-horticulture production. As pointed out by Sikka, the regions which are ideal for this are those where seasonal waterlogging occurs during the monsoon. The reason is that high water table conditions would reduce the requirement for replenishing the fish ponds with pumped or diverted water. The high water table areas in North Bihar plains, which have a rice-wheat system of farming, would be ideal for such approaches.

Multiple use systems of dyke and pond for horticulture-fish farming would be ideal for the waterlogged areas of coastal Orissa (Puri District), Surat and Valsad districts in South Gujarat and Alleppey in Kerala, which not only experience high rainfall, but also receive large amounts of canal water. Also, these areas are dominated by paddy as the main crop and the yields are not very high. Hence, farmers will have strong economic incentives to adopt fish and horticulture production. In all these pockets, raised bunds can be used for growing banana.

Secondary reservoir cum fish pond for improving water productivity in paddy farming can be adopted in coastal Orissa, coastal Andhra Pradesh, and North Bihar, which receive excessive canal water for irrigating paddy. High water table conditions would ensure not only low costs for the energy required for pumping groundwater, but also increased irrigation return flows (Kumar et al. 2008f). But, it is to be kept in mind that in all these situations, it is not the water productivity which would motivate the farmers to go for fisheries, duckery etc., but the enhanced returns from the land. The reason is that all the locations that are ideal for MUSs, water is available in plenty while land is scarce.

Water Productivity Improvement in Rain-fed Areas

Amarasinghe and Sharma (Paper 2, this book) shows that there are two ways in which rain-fed areas can experience water productivity improvement: 1) through a shift from low yielding short duration rain-fed crops to high-yielding long duration crops requiring irrigation with increase in ET as well; and 2) reducing the yield gap of certain long duration food grain crops through agronomic inputs. Most of India's so called rain-fed areas are in the central Indian belt and south Indian peninsula. Vast improvements in crop yield and water productivity are likely to occur in the central Indian belt encompassing the basin areas of Narmada, Tapi and Mahanadi. Water productivity improvement for food grains in this region is also likely to take place through farmers shifting from short duration rain-fed course grain crops and cash crops (like cotton) to long duration food grain crops which consume more water, but have high water use efficiency. This will be enabled by supplementary irrigation.

The changes will show up on the cropped area of winter crops viz., wheat and cotton, and kharif paddy receiving supplementary irrigation, which will lead to an enhanced production and water productivity of food grain crops in the region (Amarasinghe and Sharma, Paper 2 of this book). In the case of Narmada, this would be the result of large-scale water resource development projects, which are being completed or are coming up in the basin. For the other basins, this could result from small-scale water harvesting interventions, as viable sites for large reservoirs are already tapped in these basins. But, the water harvested through such structures will have to be diverted for growing water-efficient crops for the schemes to be viable (Kumar et al. 2008b). Again, similar changes are likely to occur due to exploitation of water from the Godavari Basin, which still has large un-utilized potential of surface water (GOI 1999), large-scale diversion of which is already planned. All these would result in more water being diverted and used in agriculture. As per GOI, 1999, the gross irrigated area in the Godavari Basin would be 11.013 m ha by the year 2050 covering parts of the four states of Madhya Pradesh, Maharashtra and Andhra Pradesh. This is a quantum jump of 7.0 m ha from the current level. Most of this expansion is going to come from increasing cropping intensity in the basin states, but, its positive impact on crop water productivity would be major. Therefore, it would actually reduce agricultural water demand in the country. Going by the estimates provided by Amarasinghe and Sharma (Paper 2, this book), this can cover 281 districts.

According to Amarasinghe and Sharma (Paper 2, this book), in a total of 117 districts, the water productivity of food crops can be enhanced by reducing the yield gap. Since the ET value for these crops is not going to change, this will have no impact on the water supply requirement, but it can bring down the overall water demand for food grain crops. But, this is not going to be easy as these are very backward regions, where farmers lack resources to invest in high yielding varieties and fertilizers and pesticides. The agro-ecology in these regions also poses challenges, due to floods.

In summary, many arid and semi-arid regions in India, where water development is already high, there seem to be a higher scope for improvement in water productivity in agriculture. It will come through MI systems, water delivery control, improving quality and reliability of irrigation, and economically efficient water allocation within and across the regions. This can significantly reduce water demand in agriculture, provided institutional mechanisms are in place for rationalizing the allocation of water to this sector.

Whereas in other regions, where water resources are not much developed, irrigation water use is quite low. At the same time, the yields, crop water productivity and crop production are also disproportionately low. The current production is not able to meet the cereal demands, and agricultural growth needs in these regions. Here, the demand for water and land for meeting food production can actually be substantially reduced, if the water resources in these regions are properly harnessed and allocated to agriculture. That in turn would help enhance yields and water productivity. In a nutshell, less water would be required to meet the cereal and agricultural growth requirements. But, how much of water actually gets consumed depends on the investments in development of water and institutions for water allocation.

Summary

To summarize, water productivity assessment in countries like India should involve complex considerations of the ‘scale of analysis’; food security and regional economic growth impacts; environmental costs and benefits; and, an objective of water productivity analysis. With changes in considerations, the assessments would also change. Integrating these considerations in the technological, institutional and policy interventions to enhance agricultural water productivity would mean limited scope for raising agricultural water productivity in many cases, and greater opportunities in certain other cases.

Nevertheless, as studies presented in this book show, there are several opportunities for improving water productivity in both irrigated and rain-fed agriculture in India. These measures together cover vast areas of the crop land in the country. Measures such as water delivery control, including deficit irrigation; improving quality and reliability of irrigation water supplies; optimizing the use of fertilizers; use of micro- irrigation systems; encouraging multiple use systems; and, growing certain crops in regions where they secure high water productivity, offer great potential for improving water productivity in irrigated agriculture. Micro-irrigation alone can cover an area of 5.9 m. ha, if we just consider the well-irrigated areas that are most ideal for MI adoption. There is 23.6 M ha of canal-irrigated area in the regions where MI can improve water productivity. But, for this, the water supply systems have to be made amenable to MI adoption. The first step to bring these areas under MI systems is to either change the delivery practices or to increase the economic incentives. Economic incentives for MI adoption in canal commands can be improved by increasing the price of irrigation water, in that high prices for irrigation water would affect cost saving as a result of applied water saving.

Measures such as ‘water delivery control’ and improvement in quality and reliability of irrigation are relevant for regions such as Punjab, Haryana and intensively canal irrigated pockets of Madhya Pradesh, Maharashtra and peninsular India (Kumar et al. 2008c; Palanisami et al. 2009). Also, there are many basins like the Narmada, Indus, Sabarmati and Cauvery where certain pockets can be earmarked for growing certain crops with a relatively lesser amount of water, but can give higher yield and water productivity by virtue of the climate (Kumar and Singh 2006). This needs to be explored for agro-climatic planning for crops, while the constraint imposed by land availability also needs to be examined.

Besides this, as illustrated through the cases of Punjab and North Gujarat, farming system improvement can raise agricultural water productivity in economic terms. While in the case of Gujarat, it will be a shift from milk production to orchards and cash crops, in the case of Punjab, it was a shift from paddy-wheat system to orchards and vegetables.

But, the ability of these regions to move away from the low water-efficient conventional cropping system would depend very much on the pressure on these regions for food self-sufficiency. The regions which are largest water users in agriculture are Punjab, Haryana, Andhra Pradesh, Gujarat and Maharashtra. Of these, Punjab, Haryana and Andhra Pradesh are the largest contributors to India’s granary (Kumar et al. 2008d). Crop shift from food grains to water-efficient fruits and vegetables and cash crops (such as cotton, groundnut) in these regions would have negative implications for India’s food security. But, regions such as Madhya Pradesh (MP) and parts of Andhra Pradesh (AP), which have rain-fed cereal crops such as wheat and paddy in MP and paddy in AP, will be able to enhance the production through irrigation facilities. This, in turn, would ease the pressure on groundwater resources in the existing cereal producing regions such as Punjab, Haryana and parts of Andhra Pradesh. As regards Gujarat and Maharashtra, the possibility for a crop shift to improve water productivity exists.

As shown by Amarasinghe and Sharma (Paper 2 of this book), there are vast areas under rain-fed production in central India’s tribal belt and peninsular India, extending over 211 districts, which could experience quantum jumps in crop yields and water productivity through supplementary irrigation. These are essentially areas, which are already experiencing or going to see large water development projects for irrigation. But, some of the basins in these regions, where water resources are already utilized to their full potential, have to be left out as they won't benefit from the gain in water productivity. The impact of increased irrigation in these regions would mainly be on cereals such as wheat and paddy, and cotton.

Introduction of multiple use systems would help enhance water productivity in selected pockets in India but, these pockets are characterized by water abundance and land scarcity. The important consideration for farmers to go for such farming systems would be increasing returns from every piece of land, which is either productive or unproductive at present. Successful introduction of such farming systems in those regions will have a significant impact on agricultural growth and rural poverty.

In the estimates of the irrigated area that can be brought under micro-irrigation, we have left out the areas that are highly susceptible to waterlogging conditions as areas not suitable for micro-irrigation systems. The reason is water-saving is not a consideration here, and the adoption of MI technology will not lead to any improvement in water productivity. In such areas, interventions to improve applied water productivity, which perhaps would also increase productivity of depleted water through micro-irrigation, water delivery control and improvement in quality and reliability of water would make sense from an environmental perspective and would give larger social benefits.

In the intensively canal irrigated areas, while introducing measures for improving the quality and reliability of canal water supplies and water delivery control, it is important to see the changes in the groundwater conditions. The reason is that the returns from groundwater irrigation are high in these regions, and canal return flows sustain the groundwater ecology in such areas. As Dhawan (2000) notes, reduction in return flows resulting from water management interventions in canal irrigation would threaten the sustainability of well irrigation (Dhawan 2000) though that would raise crop water productivity. But, this has to be compared against the saving in opportunity cost of leaving the water underground, which is equal to the saving in the cost of energy required for pumping out the return flows.

Long, Medium and Short-term Policy Measures

To sum up, much less water would be required to meet the increased demand for cereals and other agricultural outputs if water productivity in agriculture could be raised. But, how much water actually gets consumed in the sector would depend on the investments in water development, and institutions for water allocation. Having said this, it is important to recognize the constraints to improving water productivity. These constraints can be classified into those which are physical, technological and infrastructural; institutional and policy-controlled; and, market-related. The policy constraints concern the pricing of water used in canal irrigation and electricity used in well irrigation, whereas the institutional constraint lies in the lack of well-defined water rights for both surface water (Kumar and Singh 2001) and groundwater (Kumar 2005). Both these factors leave minimum incentives for farmers to invest in measures for improving crop water productivity as such measures do not lead to an improved income in most situations (Kumar et al. 2008c).

The electricity used for groundwater pumping needs to be metered and charged on a pro rata basis in regions where well irrigation is intensive for the energy costs to reflect the actual consumption. Gujarat has already started doing this, wherein nearly 40 % of the agricultural connections are metered. The introduction of pro rata pricing of electricity in the farm sector, and volumetric pricing of canal water for irrigation, are the most important fiscal measures for improving water productivity in agriculture. By doing this, the farmers would be confronted with a marginal cost of using electricity/groundwater and canal water for irrigation. Introduction of pro rata pricing would also encourage well irrigators to adopt MI systems, which can serve as medium-term measures.

Enforcement of water rights is the most important institutional reform needed in the groundwater sector (Kumar 2007; Saleth 1997), but, this would be rather a long-term measure, as allocating water rights for individual users, and enforcing the same would be an arduous task (Kumar 2000; Kumar 2007). Also, there are practical issues in enforcing water rights as rights can be often 'correlative', especially in hard-rock environments (Saleth 1997). But, to begin with, the latest technological advancements in energy use metering through the use of mobile phone and internet technology can be used to monitor or restrict the use of electricity by farmers on the basis of various socioeconomic or hydrological considerations, with minimum transaction costs (Zekri 2008).

Short-term Institutional and Policy Measures

Targeted Subsidies for MI Systems: Today, subsidies for MI are available everywhere, without any due consideration to the social costs and benefits. Subsidies are generally provided when they are positive externalities associated with the use of a product. In the case of MI systems, the positive externalities are induced water saving. The extent of real water saving that is possible with MI systems is a function of the soil, climate, geo-hydrology and type of technology used. Subsidies should be made available only in regions where the positive externalities induced by the use of MI systems on society are likely to be high. This would help scale up the adoption of the technology in the areas where it creates maximum benefits.

Provision of Subsidies for Intermediate Storage Systems: In canal command areas, the better the yield that farmers can get with improved control over irrigation water, itself, could justify the investments needed for intermediate storage systems like the 'diggies' in Rajasthan (Amarasinghe et al. 2008). But, provision of subsidies would create an additional incentive for them to adopt MI systems, and shift to crops that have high water productivity.

Improving the Processing and Marketing Infrastructure for Agricultural Produce: To avert the risk of a price crash in the market and for value addition, adequate processing and marketing infrastructure for the perishable agricultural commodities is important. Only this can ensure that a large number of farmers from one region stick to producing highly water-efficient fruits and vegetables that involve high production and market risks.

Improvement in Farm Power: It is well established now that the returns from well irrigation are more elastic to the quality of power supply than its cost. Improved quality of power supply would not only help farmers to secure higher returns from farming owing to greater control over irrigation, but also allow them to use water-efficient irrigation systems such as the MI.

Improvement in Electricity Infrastructure in Rural Areas: In many rural areas of eastern India, power supply infrastructure is in bad shape. Securing a power supply connection is extremely difficult. As a result, the electric well owning farmers charge 'monopoloid prices' for water from the small and marginal farmers. The high cost of irrigation water prevents the water buyer farmers from investing adequately for irrigation and optimal use of other inputs. The result is that they obtain poor yields. Improved electricity infrastructure would reduce the monopoloid prices' for water, thereby giving more flexibility to the farmers in investing adequately for other inputs.

Concluding Remarks

To conclude, water productivity enhancement in agriculture is not only relevant, but also very crucial in meeting future water demands for agriculture and other sectors. There are several constraints in enhancing water productivity in agriculture. But, there are several opportunities too. The constraints can be reduced and opportunities enhanced through appropriate institutional and policy interventions. It is time that India's water policymakers shed the myopic view and start thinking about these policy issues more seriously considering the larger economic and social benefits of policy reforms. As Kumar (2007) notes, one such view is that raising power tariff would adversely affect the economic prospects of farming. In that context, understanding the latest technological advancements in monitoring and metering electricity consumption is very important. The pre-conceived notion that electricity metering in rural areas involves huge transaction cost has to be replaced by an informed understanding. Also important are the new concepts in water management such as water and energy productivity and their various determinants.

Water productivity improvement would definitely reduce the need for future investments in new water resource development projects in some regions. But, the extent of reduction in demand for additional water for meeting future needs will not be the same as the scale of enhancement in water productivity achieved. On the contrary, it might result in more water being available for environmental uses or other sectors in some regions. The other outcomes of water productivity improvement will be in terms of reduced poverty due to a rise in farm income in the agriculturally backward regions; reduced environmental stresses caused by excessive pumping of groundwater or diversion of water from streams/rivers; better availability of water from basins for allocation to environmental uses; and freeing up of a large amount of cultivated land under rain-fed production resulting in increased stream flow generation from catchments. This is what makes water productivity improvement in agriculture an extremely attractive proposition for a developing economy like India.

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ISBN 978-92-9090-712-1