



The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

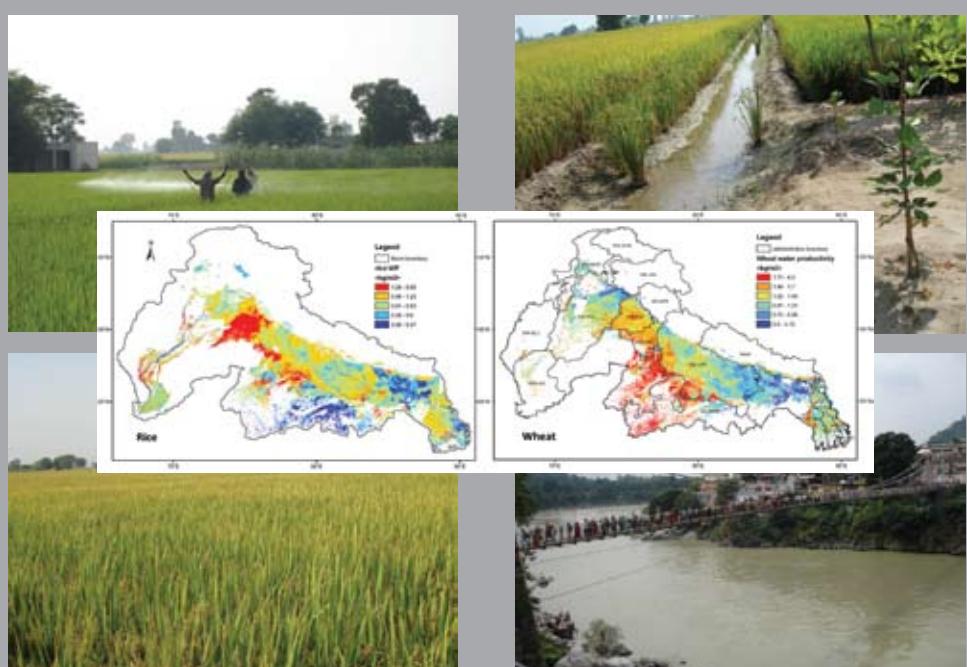
AgEcon Search
<http://ageconsearch.umn.edu>
aesearch@umn.edu

Papers downloaded from AgEcon Search may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.

No endorsement of AgEcon Search or its fundraising activities by the author(s) of the following work or their employer(s) is intended or implied.

An Assessment of Crop Water Productivity in the Indus and Ganges River Basins: Current Status and Scope for Improvement

Xueliang Cai, Bharat R. Sharma, Mir Abdul Matin, Devesh Sharma and Sarath Gunasinghe



Research Reports

The publications in this series cover a wide range of subjects—from computer modeling to experience with water user associations—and vary in content from directly applicable research to more basic studies, on which applied work ultimately depends. Some research reports are narrowly focused, analytical and detailed empirical studies; others are wide-ranging and synthetic overviews of generic problems.

Although most of the reports are published by IWMI staff and their collaborators, we welcome contributions from others. Each report is reviewed internally by IWMI staff, and by external reviewers. The reports are published and distributed both in hard copy and electronically (www.iwmi.org) and where possible all data and analyses will be available as separate downloadable files. Reports may be copied freely and cited with due acknowledgment.

About IWMI

IWMI's mission is to improve the management of land and water resources for food, livelihoods and the environment. In serving this mission, IWMI concentrates on the integration of policies, technologies and management systems to achieve workable solutions to real problems—practical, relevant results in the field of irrigation and water and land resources.

IWMI Research Report 140

An Assessment of Crop Water Productivity in the Indus and Ganges River Basins: Current Status and Scope for Improvement

*Xueliang Cai, Bharat R. Sharma, Mir Abdul Matin, Devesh
Sharma and Sarath Gunasinghe*

International Water Management Institute
P O Box 2075, Colombo, Sri Lanka

The authors: Xueliang Cai is a Researcher-Water Resources and Remote Sensing based at the Southern Africa office for the International Water Management Institute (IWMI) in Pretoria, South Africa (x.cai@cgiar.org); Bharat R. Sharma is Principal Researcher - Water Resources and Head of the New Delhi office of IWMI, India (b.sharma@cgiar.org); Mir Abdul Matin, who was a former Manager of the RS/GIS Unit and based at IWMI headquarters in Colombo, Sri Lanka, is now with the University of New Brunswick, Canada (mirmatin@gmail.com); Devesh Sharma, formerly a consultant at the New Delhi office of IWMI, is now Assistant Professor at TERI University, New Delhi, India; and Sarath Gunasinghe is GIS/RS Assistant based at IWMI headquarters in Colombo, Sri Lanka (s.gunasinghe@cgiar.org).

Cai, X.; Sharma, B. R.; Matin, M. A.; Sharma, D.; Gunasinghe, S. 2010. *An assessment of crop water productivity in the Indus and Ganges river basins: Current status and scope for improvement*. Colombo, Sri Lanka: International Water Management Institute. 30p. (IWMI Research Report 140). doi: 10.5337/2010.232

/water productivity / crops / yields / rice / wheat / river basins / models / remote sensing / evapotranspiration / mapping / India / Pakistan / Bangladesh / Nepal /

ISSN 1026-0862

ISBN 978-92-9090-735-0

Copyright © 2010, by IWMI. All rights reserved. IWMI encourages the use of its material provided that the organization is acknowledged and kept informed in all such instances.

Cover photographs (clockwise from top left):

- (a) Irrigated rice in Punjab, India; (b) Extensive groundwater use in the Indus Basin;
- (c) River Ganges at Rishikesh, India; and (d) Irrigated wheat in the Indus and Ganges river basins
(Photo credits: Bharat Sharma, IWMI, New Delhi, India).

Superimposed maps:

Variation in rice and wheat water productivity in the Indus and the Ganges River Basin (Credit: Cai Xueliang, IWMI, Pretoria, South Africa).

Please send inquiries and comments to: IWMI-Publications@cgiar.org

A free copy of this publication can be downloaded at
www.iwmi.org/Publications/IWMI_Research_Reports/index.aspx

Acknowledgements

The authors would like to thank the National Bureau of Soil Survey and Land Use Planning, New Delhi Office, India, and a large number of farmers for their help in conducting the ground truth surveys; and Dr. Vladimir Smakhtin, Theme Leader for IWMI's research theme on Water Availability and Access, based at IWMI headquarters in Colombo, Sri Lanka, for valuable comments and suggestions on the manuscript. The constructive comments provided by Dr. Upali Amarasinghe, Senior Researcher, based at the New Delhi office of IWMI, India, Dr. David Molden, Deputy Director General-Research, based at the headquarters of IWMI in Colombo, Sri Lanka, and anonymous reviewers are gratefully acknowledged.

Project



This research study was initiated as part of the "Basin Focal Project for the Indus and the Ganges River Basins (BFP-IGB)" (PN 60) of the CGIAR Challenge Program on Water and Food (CPWF). It formed part of the wider network of the "Basin Focal Projects."

Donors

Funding for the research carried out in this report was provided by the following organizations, among others, through the CGIAR Challenge Program on Water and Food (CPWF).



UK Department for International Development (DFID)



International Fund for Agricultural Development (IFAD)



European Commission

The views expressed herein do not necessarily reflect the official opinion of DFID, IFAD and the European Commission.

Contents

Acronyms and Abbreviations	vi
Summary	vii
Introduction	1
The Study Area	3
Data and Method of Analysis	4
Basin Crop Yield, ET and Water Productivity	8
Causes for Variation and Scope for Improvement	14
Conclusions	18
References	19

Acronyms and Abbreviations

AVHRR	Advanced Very High Resolution Radiometer
CPWF	CGIAR Challenge Program on Water and Food
DEM	Digital Elevation Model
ET	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
GIAM	Global Irrigated Area Map
GIS	Geographic Information System
GLCCD	Global Land Cover Characteristics Database
IGB	Indus and the Ganges River Basins
IWMI	International Water Management Institute
LST	Land Surface Temperature
LULC	Land use/land cover
MODIS	Moderate Resolution Imaging Spectroradiometer
MVC	Maximum Value Composite
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
RS	Remote Sensing
SEBAL	Surface Energy Balance Algorithm for Land
SSEB	Simplified Surface Energy Balance
TRMM	Tropical Rainfall Measurement Mission
USGS	United States Geological Survey
WMO	World Meteorological Organization
WIST	Warehouse Inventory Search Tool
WP	Water Productivity

Summary

Understanding crop water productivity over large river basins has significant implications for sustainable basin development planning. This report presents a new approach for analysis of water productivity (WP) of rice and wheat in the Indus and the Ganges river basins, South Asia, based on the integration of readily available remote sensing, national crop productivity and land use statistics and weather data. Three major steps are involved in producing crop water productivity maps: (1) crop dominance map, (2) yield estimates, and (3) water consumption (evapotranspiration (ET)) estimates. The crop dominance map is synthesized from the relevant, and publically available, land use/land cover (LULC) maps with ground truth data. National statistics on crop area and yields are collected, and the yields are interpolated to grid level (500 meters (m) x 500 m) using Moderate Resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index (NDVI) maps. Crop ET is mapped using Simplified Surface Energy Balance (SSEB) model with MODIS land surface temperature estimates and meteorological data (minimum, maximum and mean air temperature) collected from 56 weather stations. High crop water stress is

observed at basin level in spite of high rainfall during the *Kharif* season. The basin average ET of rice and wheat is 368 and 299 millimeters, accounting for only 69% and 65% of potential ET, and 67% and 338% of rainfall of the crop growth period, respectively, measured from Tropical Rainfall Measurement Mission (TRMM). The basin average WP for rice and wheat is 0.74 and 0.94 kilograms per cubic meter (kg/m³), respectively, with significant variability. This variability generally follows the same trend as that of the crop yield regardless of changes in climate and topography. The sum of WP of rice and wheat, however, exhibits a different trend as a result of irrigation, on which wheat yields heavily rely. The scope for improvement of WP is assessed through comparison of the limited area under “bright spots” and the vast areas of low productivity “hot spots”. This comparison indicated that significant potential exists for improvements in water (and land) productivity in the middle to lower reaches of the Ganges Basin, where water is abundant but the high consumption was not converted into high crop yields. Water is the determining factor for crop yields in most areas, which, however, has to be developed in light of environmental sustainability.

An Assessment of Crop Water Productivity in the Indus and Ganges River Basins: Current Status and Scope for Improvement

Xueliang Cai, Bharat R. Sharma, Mir Abdul Matin, Devesh Sharma and Sarath Gunasinghe

Introduction

Food security is a major concern in many parts of the world including the densely populated riparian countries of the Indus and Ganges River Basins (IGB) in South Asia. The prospects for significant expansion of crop cultivation or irrigation are limited. To meet the rising food demand that will occur as a result of increasing population and changing dietary patterns, the world needs to ensure sustainable land and water productivity improvements over the coming decades (Molden et al. 2007). However, agricultural water use is facing competition from water demands from industry, domestic users, and the need to allocate water to aquatic ecosystems and environmental services. The agricultural sector is projected to receive reduced water allocation despite the increasing pressure for more food production (Kijne et al. 2003). Together, the increasing food demand and decreasing water allocation suggest that the agricultural sector has to produce more food with less water, that is, to increase agricultural WP (Cai and Sharma 2010).

Water is one of the most critical inputs to agriculture. However, the level of water use differs significantly across regions, farming systems, canal command areas and even farm plots (Molden et al. 2003). The complicated hydrological processes in areas where hydrological conditions were significantly modified by agricultural interventions make it extremely difficult to assess the performance of agricultural

water management. This is especially true in large transboundary river basins. Basin-wide WP analyses (Molden 1997) are required to measure the effectiveness of these interventions through analysis of system water demand-supply and its relation to agricultural outputs.

WP may be measured by a series of indices which describe its various aspects, e.g., physical and economic WP, irrigation WP, rainwater productivity, and ET WP. Individual indices serve various purposes. The combined use of several indices, e.g., irrigation WP and ET WP, help to better understand water uses and associated outputs. Yet, information on water supply and consumption is often inadequate. This is particularly true when groundwater extraction through private pumps is a common practice, which is the case in many parts of IGB. In this context, ET WP is a pragmatic option to assess the effectiveness of basin-wide agricultural water supply and consumption, particularly when supported by new powerful techniques and data provided by satellite remote sensing (RS).

RS provides an opportunity to observe land surface processes at large scales in a cost-effective manner (Schmugge et al. 2002). IWMI pioneered RS applications in the assessment of the performance of irrigation systems, including several studies in the Indus and Ganges basins. Thiruvengadachari and Sakthivadivel (1997) and Sakthivadivel et al. (1999) evaluated the performance of the Bhadra and Bhakra projects

in India, respectively. Bastiaanssen et al. (1999a) coupled remote sensing with hydrological models to assess the performance of irrigation systems, and Bastiaanssen et al. (1999b) used RS data to estimate both crop yield and ET for assessment of WP. The method was further developed to use the Surface Energy Balance Algorithm for Land (SEBAL) to determine both crop yield and ET, by improving the yield estimation module (Bastiaanssen and Ali 2003). The RS-based analysis requires very little ground data, and enables more detailed land and water studies in multiple spatial and temporal domains, which otherwise are constrained by conventional data limitations.

RS analysis, however, also has limitations due to data quality and cost. RS analysis of crop conditions and water consumption requires complicated site-specific parameterization processes linked to extensive ground observations. Another issue is the frequently noticed differences between RS interpretations and national statistical data. These differences limit the use of RS-inferred recommendations in practice, and statistical data often remains the preferred choice (Frolking et al. 2002). Combined uses of RS interpretations and statistical data provide a potential solution to address these issues by extending individual strength to each other.

Integration of RS with various data sources can bring consistency and facilitate developing a large-scale regional analysis. Statistics and weather data from the public domain are widely available for a large part of the world. For example, the AQUASTAT information system of the Food and Agriculture Organization of the United Nations (FAO) is a comprehensive dataset providing statistical data on agriculture, water and land (www.fao.org/nr/water/aquastat/main/index.stm). Subcountry level data are published by respective authorities in most countries. Historical and near-real time weather data are collected from weather stations of national meteorological

services. Some of this data is exchanged through the CLIMAT network, which is part of the World Meteorological Organization's (WMO) Global Telecommunication System (GTS). These datasets are readily available with relatively good coverage for global to regional studies. The United States Department of Agriculture (USDA) has made a good example of assimilating different remote sensing, statistics and ground observations to monitor and estimate precipitation, soil moisture, and crop conditions (Reynolds 2010). Such an approach to make use of various available datasets has great potential to contribute to comprehensive and cost-effective analysis of the complex systems.

As part of the 'Basin Focal Project for the IGB' supported by the CGIAR Challenge Program on Water and Food (CPWF), a study has been carried out to assess the basin agricultural water management performance to reveal the implications for food security while securing sustainable development of the basin. This research report assesses the agricultural WP of the basin with focus on the predominant rice and wheat cropping system. The report presents a new approach to integrate remotely sensed imagery, meteorological data, ground survey, and national crop and land use census to assess crop water productivity at basin scale. The causes for its variations and potential for improvement were also analyzed. The section, *The Study Area*, briefly describes the characteristics of the study area. The section, *Data and Method of Analysis*, details the data sources and method of analysis. We present the detailed results of basin crop yield, ET and water productivity and the related maps in the section, *Basin Crop Yield, ET and Water Productivity*, followed by the causes for variation and scope for improvement of water productivity in the section, *Causes for Variation and Scope for Improvement*. Major conclusions, recommendations and suggestions are presented in the section, *Conclusions*.

The Study Area

The IGB covers a vast area of 225 million hectares (Mha) including all of Nepal, significant parts of India, Pakistan, Bangladesh and small parts of China and Afghanistan (see Figure 1). The basin originates from the southern slope of the Himalayas and Hindu Kush and extends southwards to the great plains of the Indus and the Ganges in India and Pakistan, and then further extends in two directions: the Indus towards the Arabian Sea on the southwest and the Ganges towards the Bay of Bengal on the southeast. Diverse topographic, climatic and soil conditions exist in the basin. The climate is strongly characterized by monsoons with annual average precipitation varying from less than 100 mm to 4,000 mm. Most of the rainfall occurs from June to October (*Kharif* season) as opposed to the relatively dry season from November to May (*Rabi* season).

The IGB is the most populous river basin in the world with a population of 747 million (2001, now estimated at 1 billion). The four major countries, India, Pakistan, Bangladesh and Nepal, are all experiencing fast population growth which imposes high pressure on regional water supply and food security. Approximately three-quarters of the total population live in rural areas and about 30.5% lives below the poverty line (Sharma

et al. 2010). With the total population of the Indian portion of the IGB projected to increase by 58% by 2050, the per capita renewable water resources are estimated to decrease from 1,971 cubic meters (m^3) to 1,254 m^3 , which is far below the water stress line of 1,700 m^3 . The Indus in Pakistan is already a closed basin (Sharma et al. 2008). Further, climate change is inducing many uncertainties in precipitation patterns and snowmelt from the Himalayas.

Agricultural intensity in the IGB is extremely high. More than 50% of the total drainage area is cultivated. Rice-wheat rotation is the predominant cropping system, mixed with cotton, sugarcane, pulses, millet and jute, etc. Extensive irrigation is practiced in the major food production zones for paddy rice (*Kharif*) and wheat (*Rabi*). A large quantity of surface water is diverted for irrigation through canals of the Indus Basin Irrigation System in Pakistan and Bhakra Irrigation System in India. However, groundwater use through numerous pumps is the most popular practice in India and Bangladesh (Shah et al. 2006). It is difficult to monitor and account for the actual water diversion and depletion. However, researches have already disclosed overexploitation of groundwater in the northwest of India which imposes serious

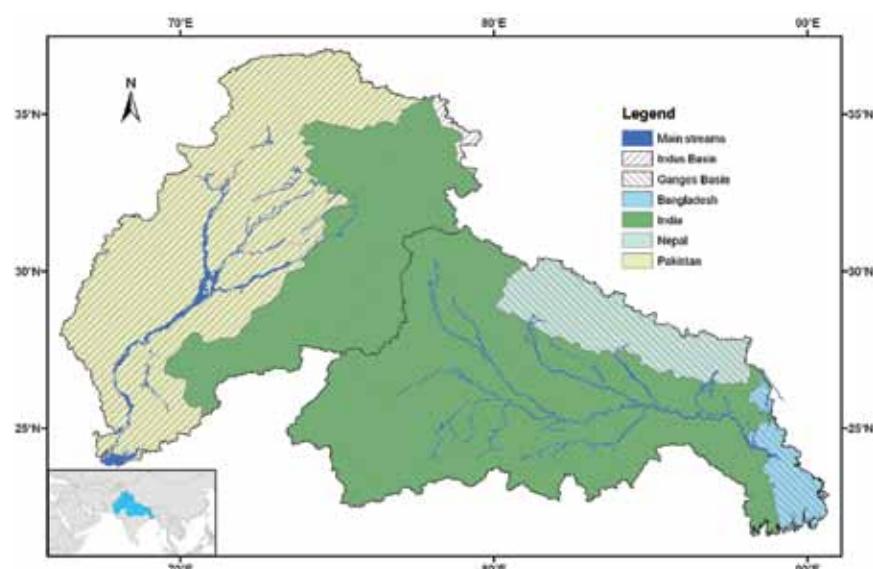


FIGURE 1. The geographic location of IGB and the riparian countries.

threats to sustainable development (Rodell et al. 2009). Meanwhile, lack of irrigation and drainage facilities causes low productivity in the downstream of the Ganges. Severe floods and

droughts occur frequently in these areas. Overall, the basin is under extreme pressure due to both water scarcity and regional development (Sharma et al. 2010).

Data and Method of Analysis

This section introduces the method and datasets that were used to map basin-scale crop water productivity for rice and wheat through a data assimilation approach. Three major steps were involved including synthesis of crop dominance map, yield mapping, and crop ET mapping, which together lead to the final WP map. The crop dominance map was produced taking into consideration the cropping patterns of rice, wheat, cotton and sugarcane. The other three steps were carried out for rice and wheat separately.

Crop Dominance Map

Water consumption and productivity analysis requires specific information on crop location and growth season. However, an explicit crop type mapping at basin scale is difficult given the technical and resource limitations. Instead of an individual crop type mapping, the crop dominance map focuses on the dominant crops and is, hence, relatively easy to produce. Such a map does not specifically distinguish each crop from another. Rather, it gives the major crops grown in the region for the specified period. As this study focuses on the predominant crops of rice and wheat, a crop dominance map will be able to serve the purpose. In this study such a map is synthesized through three existing maps backed with statistical data and ground truth information.

Many efforts have been denoted to map LULC using remote sensing at global and regional scales, some of which cover the IGB (for example, Leff et al. 2004; Arino et al. 2007;

Becker-Reshef et al. 2010). Three LULC maps were used in this study. They are: (a) the USGS Global Land Cover Characteristics Database (GLCCD) of 1992-1993 (Loveland et al. 2000), (b) the IWMI Global Irrigated Area Map (GIAM) of 2003 (Thenkabail et al. 2006), and (c) the University of New Hampshire South Asia Rice Map of 2002 (Xiao et al. 2006). These three maps were chosen because: (a) the GLCCD (1 kilometer (km) resolution) is a well-known global dataset extensively used worldwide. It gives a good general indication of land use in the basin; (b) the South Asia rice map and the GIAM are highly relevant to the study. The South Asia rice map is generated from MODIS 500 m products for South Asia and dedicated to the major crop, rice. The GIAM, also from MODIS 500 m for the same region, focuses on irrigated areas which are mainly under rice and wheat cultivation. However, these three maps were produced through different approaches and have different interpretations. For example, the rice map has only one class which is marked as 'paddy field'; the GLCCD map has five classes for agriculture but does not specify crop types; and the GIAM map focuses on the irrigated areas.

We compiled a dataset using the three LULC maps. MODIS 16-day 250 m time series NDVI products were downloaded via the NASA Warehouse Inventory Search Tool (WIST) (<https://wist.echo.nasa.gov/api/>). Two ground truth datasets were used. One with 57 samples was collected in 2005, and another with 175 samples in October 2008. Both datasets collected information on crop area fraction within a 90 m x 90 m square through

eye estimate. Crop rotation information was acquired through farmer survey. Digital Elevation Model (DEM), administrative boundaries, and agro-climatic zones were also collected from available online open sources.

A hierarchical approach was developed to synthesize the three LULC maps (Figure 2). The three maps were overlaid with each other, resulting in a number of segments for the basin. The commonly agreed segments by the three maps (or two maps when it is a non-paddy field) were identified directly. In case of a discrepancy, the paddy rice map was given the highest confidence so major rice areas are directly extracted. However, crop rotation information, e.g., the crops in the *Rabi* season, was taken from the GIAM map in consultation with the MODIS NDVI time series image mega file. Some other major crops, e.g., sugarcane, cotton and wheat, which fall outside the paddy rice map but inside the GLCCD agricultural classes, are directly taken from GIAM. Nonagricultural areas were directly masked out as this study focused mainly on cropland. A significant proportion of mixed agricultural area is left to be further analyzed.

ISODATA clustering algorithm (ERDAS 2009) backed with SMT (Spectra Matching

Technique) (Thenkabail et al. 2007) was used to classify the remaining agricultural areas. The total remaining areas were first classified into 20 subclasses. SMT was then adopted for class identification and its naming. In SMT, the ideal crop spectra were obtained from ground truth data which requires continuous monitoring of selected points. This study modified the process by introducing crop coefficients (K_c). Cai and Cui (2009) have observed a good correlation between crop K_c variation, when normalized to a scale of 0 to 1, and NDVI development. This similarity makes the K_c curves ideal spectra to represent the crop vegetation development. Figure 3 illustrates the temporal variation of K_c values of major crops in the IGB (Ullah et al. 2001). Time series NDVI signature of each class is then compared to these ideal spectra curves and clustered based on a similarity threshold. Theoretically, all crops can be identified based on this method. However, the spatial resolution of MODIS NDVI images are 500 m, which means a lot of mixed pixels exist in the highly heterogeneous IGB. Hence, crops with similar growth periods were grouped together, resulting in a number of classes that include several crops as “crop groups.”

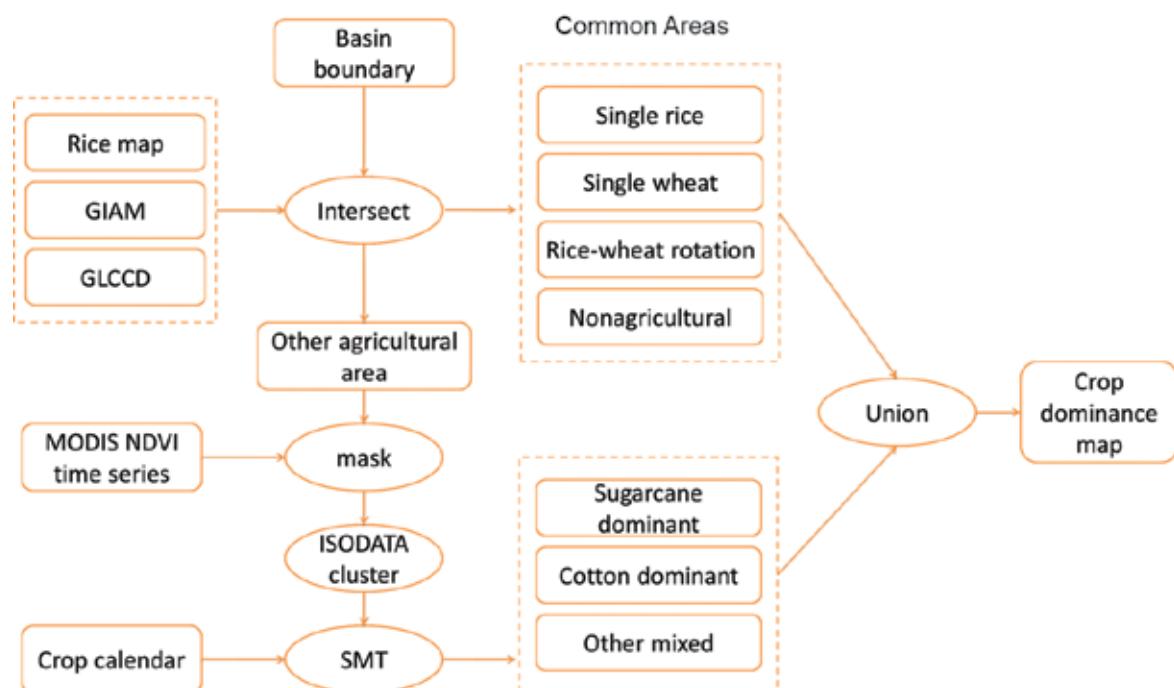


FIGURE 2. The methodology flowchart to synthesize the crop dominance map.

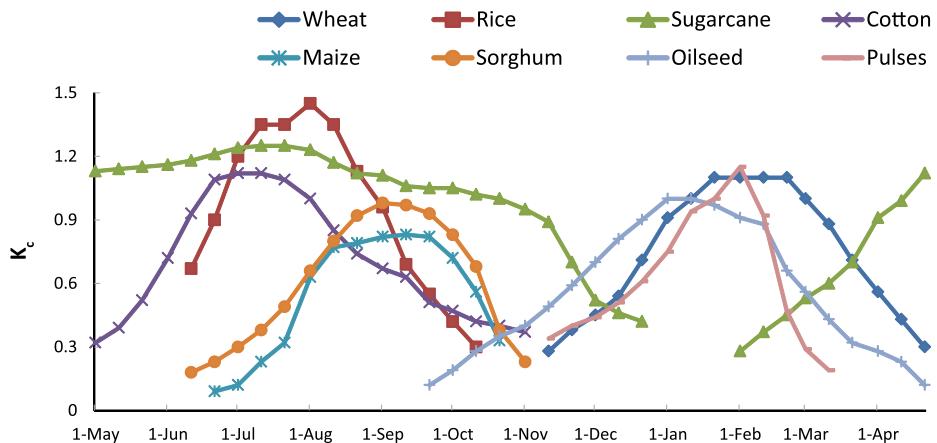


FIGURE 3. Crop coefficients of major crops in the Indus and Ganges river basins (Source: Ullah et al. 2001).

Integrating Census and MODIS Data to Map Rice and Wheat Productivity

We combined the yield statistics and satellite imagery to bring consistency, and to simplify the RS interpretation processes by maximizing the use of various available data. The yield maps of rice and wheat were produced separately in two steps. First, a polygon-based district average yield map was generated from statistical data. Then the map was extrapolated to grid level using MODIS NDVI products of the crop heading stage. The yield map of district level is straightforward to produce as crop production data are often collected and/or reported at multi-administrative level. However, the actual water consumption and crop performance are dependent on many factors such as topography, soil, water, climate and on-farm management practices, which do not necessarily correspond to administrative boundaries. Therefore, it is necessary to identify the actual boundaries of crop performance variations, which could be easily assessed from pixel-based raster maps.

The national statistical data were collected from country sources. The dataset includes district-level crop area, yield and production for India, Pakistan, Bangladesh and Nepal. The time period of the data is mainly years 2005-2006 with a few districts varying from 2001 to 2004. Yield and production of these districts were then estimated for 2005-2006 with state-level data using linear algorithm assuming a fixed

percentage of district production to state-level production.

Linear relationship between crop yields and NDVI at crop heading stage are observed and validated in a wealth of literature (for example, Grotel 1993; Bastiaanssen et al. 1999b). In India, Thiruvengadachari and Sakthivadivel (1997) found the highest correlation for rice with a coefficient of determination statistically significant at 0.76. The linear relationship could be generally expressed as shown in Equation (1) below.

$$Yield = a \times NDVI + b \quad (1)$$

The two parameters *a* and *b* were determined by replacing yield and NDVI using district average values (from statistics and MODIS NDVI products at crop heading stage, respectively).

To use Equation (1), the crop heading stage and NDVI values at this stage need to be determined. The main growth period of paddy rice in the IGB is from mid-June to early October with significant variations depending on weather, water conditions and farmers' cultivation practices. Assuming an average of 80 days after transplanting (Oza et al. 2008), the rice heading stage is determined to be from August 25th to September 9th. In this case a window of 16 days is given to allow for capturing the variation in crop growth. Sixteen MODIS NDVI images, one day each, were downloaded from WIST. To ease the heavy clouds around this period, which show low NDVI values, and also to extract maximum

NDVI values which represents the crop heading stage, the 16 images were compared pixel by pixel to extract maximum values into an MVC (Maximum Value Composition) image. Non-rice-dominant areas are masked out using the crop dominance map. District average NDVI values for rice are then calculated and input into Equation (1) together with district average rice yield, leading to a 250 m x 250 m resolution yield map of rice (*Kharif*).

Similar procedures were undertaken to produce a yield map of wheat, of which the heading stage was determined to be from February 14th to March 2nd (Bastiaanssen et al. 1999b). The producer's prices for rice and wheat at the local market were converted into US dollars per tonne and used to calculate productivity in economic terms.

Simplified Surface Energy Balance (SSEB) Model for Mapping Evapotranspiration

The SSEB model (Senay et al. 2007) combines RS and meteorological data to estimate actual ET. Models like SEBAL and METRIC (Mapping Evapotranspiration at High Resolution with Internalized Calibration) assume that the differences in temperature between land surface and near-surface air vary linearly with Land Surface Temperature (LST). This assumption is further extended in the SSEB model by stating that latent heat flux (actual ET) also varies linearly with LST. This assumption is based on the relation that the differences in temperature between the soil surface and air varies linearly with soil water (Sadler et al. 2000), which is widely used in crop water modeling to deduce actual ET from potential ET (Allen et al. 1998; Senay and Verdin 2003). The model has been validated in China with SEBAL (Cai and Cui 2009), in the USA with METRIC and SEBAL (Senay et al. 2007) and with lysimeteric studies (Gowda et al. 2008). The model does not require parameter calibration and, hence, greatly reduces the dependence on parameterization and calibration, which is important for large-scale operational monitoring.

The model also employs the hot pixel and cold pixel approach to represent "no ET" or "maximum ET". The actual ET (ET_a) of other pixels is linearly distributed between the range of hot pixel ($ET_a = 0$) and cold pixel ($ET_a = \text{potential ET}$), resulting in a proportional ET fraction value (ET_f) for each pixel as expressed in Equation (2).

$$ET_f = \frac{T_H - T_x}{T_H - T_c} \quad (2)$$

where: ET_f ranges from 0 to 1, T_H and T_c are the temperatures of hot and cold pixels, respectively, and T_x is the surface temperature of any given pixel on the image. Using this approach an ET fraction map could be generated based on the LST map from thermal imagery. However, apart from the hot pixels with no ET, another "anchor pixel" needs to be identified to determine the slope. In the SSEB model, it is proposed to adopt reference ET (ET_0) calculated from weather data as maximum ET corresponding to cold pixels. The ET_a of day i ($ET_{a,i}$) can be generated by multiplying ET_f with ET_0 of day i as shown in Equation (3).

$$ET_{a,i} = ET_0 * ET_f \quad (3)$$

where: ET_0 is the ET for reference vegetation (alfalfa or grass) under certain conditions. However, the potential ET of various crops could be more or less than ET_0 after multiplying it with crop coefficient (K_c) and soil water stress factor (K_s). This study modified the SSEB model by using ET_p (which is defined as ET_0) multiplied by K_c instead of ET_0 . ET_p is the maximum crop evapotranspiration under ideal crop-growing conditions that, we assume, exist in more or less areas of a system.

ET_p maps were produced using weather data from 54 stations. While the weather stations scatter out in the basin, these data had items only on maximum/minimum/mean temperature, mean humidity and wind speed. Therefore, Hargreaves' equation was used to calculate daily ET_0 . Station ET_p was then calculated by multiplying ET_0 with K_c values of corresponding rice growth stages provided by Ullah et al. (2001). Ideally, ET_p

should be as explicit in the spatial domain as ET_f . However, this is not practical as weather data are collected from individual stations. Daily ET_p raster maps were then extrapolated from point ET_p using the tension spline algorithm.

The MODIS 8-day LST images from NASA WIST, which have gone through several calibration processes, are directly used in this study. The original images were merged into basin mosaics and converted to Earth Resources Data Analysis System (ERDAS) image format with the World Geodetic System (WGS) 84 geographic projection system. During this process, the digital numbers were also converted into LST values using the scale factor provided in the user's manual. Cloudy areas in the *Kharif* season were eliminated by replacing the values with the average of two images, one before and one after, in the nearest clear dates. Over a large scale, LST declines with the increment of altitude. An average lapse rate of 6 degree Celsius per 1,000 m observed by Thayyen et al. (2005) for the same region is used to correct LST images. Each ET_f image represents an 8-day period. The underlying assumption is that while

daily ET_0 varies, ET_f remains constant throughout the 8 days, which is acceptable when no significant land cover changes, for example, crop harvest. Daily $ET_{a,i}$ was then calculated and summed up to generate seasonal ET ($ET_{a,s}$) maps.

Water Productivity Map

The WP map expressed in terms of kilograms per cubic meter was produced by dividing the productivity map by the seasonal ET map for the crop growing area after units were adjusted. The resolution of ET and crop dominance maps was rescaled from 1,000 m and 500 m to 250 m to match the crop yield map.

The summed WP map of rice and wheat expressed in terms of US dollars per cubic meter was also produced. Yield maps were first converted into monetary terms by multiplying with local price converted into US dollars. The productivity maps of rice and wheat were then summed up and divided by the ET maps to generate the economic productivity map.

Basin Crop Yield, ET and Water Productivity

Crop Dominance Map

The crop dominance map for the IGB is shown in Figure 4. Eighteen classes were provided by the map, which include one class for rice as a single crop, one class for rice-wheat rotation as double crop, two classes for continuous crops which are mainly a mixture of rice/wheat with sugarcane, and other mixed classes.

It is observed that rice is the overwhelmingly predominant crop in the basin. Wheat, to a lesser extent, is the dominant crop in the *Rabi* season. The cotton area is mainly distributed in the Indian States of Madhya Pradesh, Rajasthan and Haryana, and in the Pakistan provinces of Punjab and Sindh. Sugarcane is mainly cultivated in the Uttar Pradesh

State of India. Other crops, e.g., pulses, maize and millet, scatter out in fragmentations mixed with the major crops. Rice-wheat is the predominant cropping pattern in the basin which accounts for 32% of cropland area. Thirty-percent of cropland area harvests only one crop a year. The average cropping intensity is 1.7, which is actually higher than the values given by various sources.

It may be noted that the map includes a significant mixture in each class and each pixel due to its coarse resolution, which adversely affects yield and ET estimates. An assessment on this pixel using ground truth data reveals that the average fraction of cropland area within a pixel is about 78%. The non-cropland area is mainly field bounds, fragmented barren land, isolated small settlements,

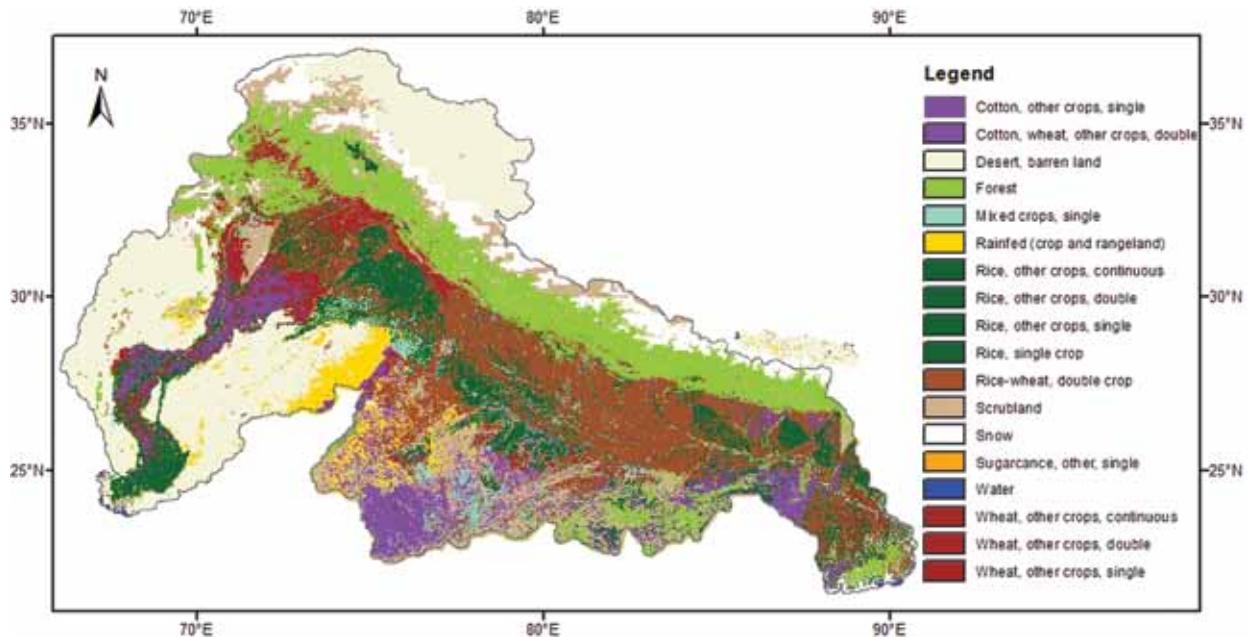


FIGURE 4. The crop dominance map (500 m resolution) of the Indus and Ganges River Basin system.

and scrubland adjacent to drainage networks. On average, there are one to four different crops in a 90 m x 90 m square at the surveyed sites. The most common crop mixture is rice and sugarcane which occurs 15 times out of the total 175 samples (including non-cropland points). The percentage of rice area in this mixture is 66%.

The 175 sample points were also used for accuracy assessment. The accuracy for cropland versus non-cropland is 96%. The average accuracy for various crop types is, however, only 76%. The accuracy for the dominant crops of rice and wheat are higher at 84% and 79%, respectively. Other mixed crops are significantly less accurate. It has to be noticed that the crop dominance is produced primarily based on 2005-2006 data while the sample points are taken in 2008. It could be assumed that the changes in cropland areas are insignificant during this period, but the crop type for any particular field may be different.

Land Productivity

Rice and wheat yield maps are shown in Figure 5. The average paddy rice yield for the Pakistan, India, Nepal and Bangladesh portions of the IGB are 2.60, 2.53, 3.54 and 2.75 tonnes/hectare

(t/ha), respectively. However, large variations exist in different areas of the basin. The “bright spot” in the Indian State of Punjab with some adjacent areas from the States of Haryana and Rajasthan (red patch in Figure 5, rice yield map) has an average yield of 6.18 t/ha, which is 2.4 times the basin average value. The “hot spots” of low-yield rice is found in the Indian States of Madhya Pradesh, Rajasthan, Bihar and in the Dhaka Division of Bangladesh with average yields of 1.18, 1.49, 2.04 and 1.97 t/ha, respectively. Furthermore, with the spatially explicit map of the pixel-level rice yield map, significant variability is observed at local scale. For example, the “bright spot” with very high yield has around 1% of area where the yield is less than 3 t/ha. The very low performance of Bihar also has a “bright spot” in a 37-km diameter cycle centered at 25.4°N, 84.44°E (southwest of Bhojpur District) with an average yield of 4 t/ha.

The basin average wheat yield is 2.65 t/ha with a high standard deviation of 1.00 t/ha. The trend of wheat yield variation is similar to that of rice. The “bright spot,” with an average yield of 4.40 t/ha, appears in the Indian States of Punjab and Haryana. However, it also stretches in the southeastern direction along the borderline of Uttar Pradesh and Madhya Pradesh States. The

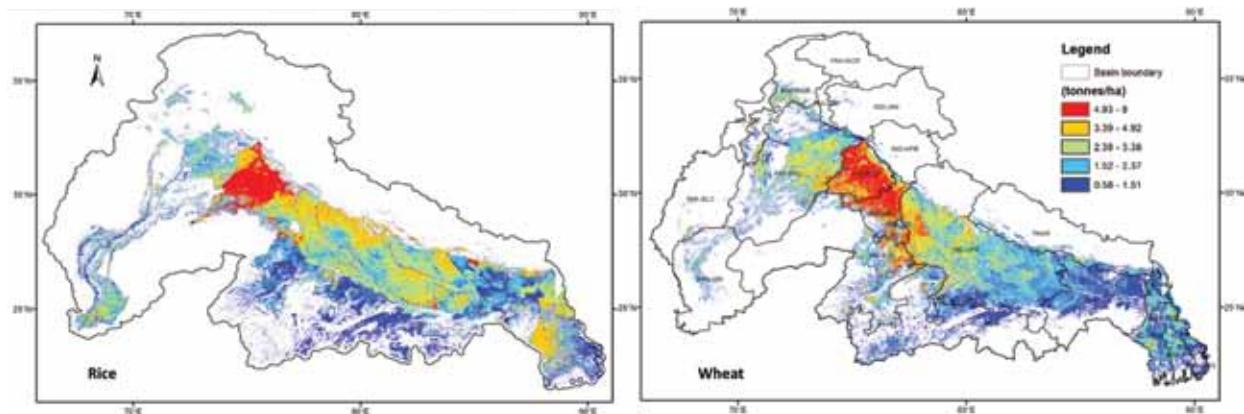


FIGURE 5. Yield maps for rice and wheat in the IGB for the period 2005-2006.

“hot spots,” with yield as low as 0.70 to 1.58 t/ha, appear in the Indian State of Bihar, part of West Bengal and Bangladesh.

Crop Water Consumption

The maps of ET_a of wheat and rice are shown in Figure 6. The basin average ET_a of paddy rice from June 10 to October 15, 2005, is 416 mm, ranging from 167 to 608 mm with a standard deviation of 104 mm (1% points were sieved). The basin average ET_a of non-rice cropland for the same period is 345 mm, with a standard deviation of 109 mm. The average ET_a of rice is significantly less than reference ET (558 mm) and rice potential ET (610 mm). Meanwhile, large areas in Bihar, West Bengal and Bangladesh also have very high ET . The possible reasons for the

high ET in contrast to low yields are discussed in the next sections.

The average wheat evapotranspiration over the main wheat growth period from November 24, 2005, to April 14, 2006, is 299 mm with a standard deviation of 61 mm (Figure 6). The ET of wheat closely follows the same variability patterns of yields. Highest values were observed in the “bright spots” of high wheat yield areas. Other areas display relatively uniform and low values.

Crop Water Productivity and the Variation

Average water productivity of rice (Figure 7) of the basin is 0.74 kg/m^3 , with minimum, maximum and standard deviation values of 0.20 , 2.04 and 0.37 kg/m^3 , respectively (1% extreme pixels were sieved). The water productivity variation closely

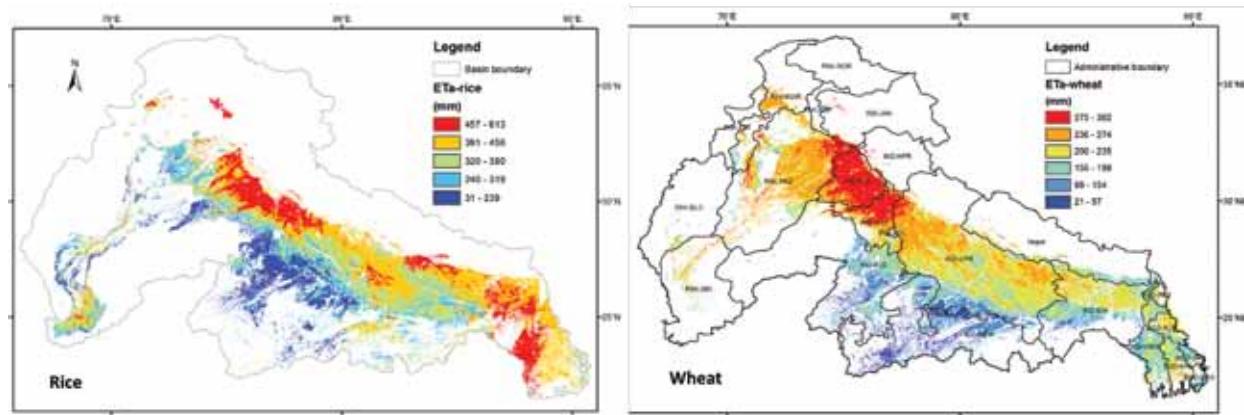


FIGURE 6. Actual evapotranspiration of rice and wheat for the period 2005-2006.

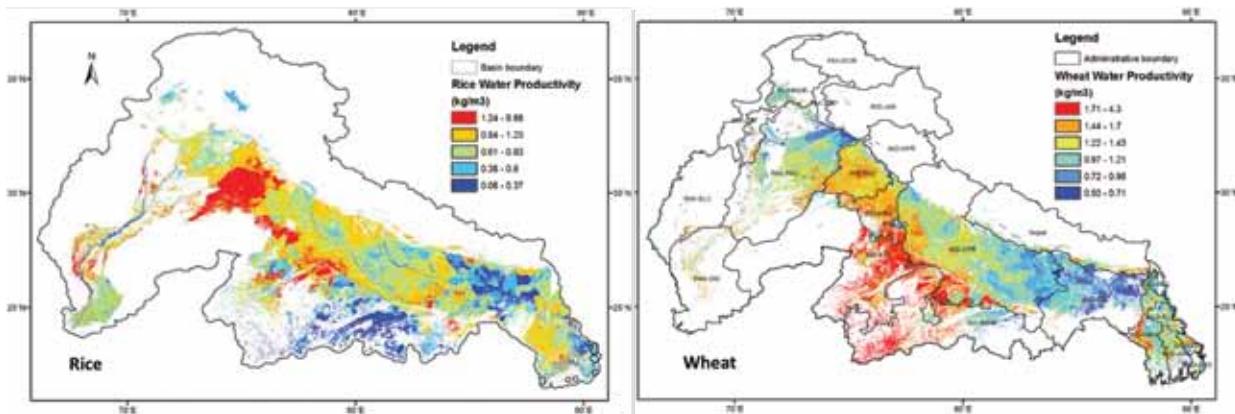


FIGURE 7. Water productivity of rice and wheat in the IGB for the period 2005-2006.

follows the pattern of yield variation. The “bright spot” of the Indian State of Punjab and adjoining areas, covering 6% of the total rice area, have very high water productivity values with an average value of 1.51 kg/m^3 . However, as much as 19% of the total rice areas have WP less than 0.5 kg/m^3 , which occur mainly in the Indian States of Madhya Pradesh and Bihar, and in the Dhaka Division of Bangladesh.

Some areas exhibit different trends in WP variation compared to yield and ET maps. A high WP strip, around 10-70 km in width, starts from 75.5°E , 29°N in the southern Haryana State and goes towards the east till the southern Bihar State in India (85.2°E , 24°N). The yield for this area is relatively low with an average value of 3.2 t/ha . However, the average ET of the same area is as low as 277 mm, making the WP relatively high. The high WP values do not suggest a satisfactory performance in this case. Rather, it provides interesting clues to examine possible water stress which could be potentially reduced by supplying supplementary irrigation during the dry spell.

The average WP of wheat is 0.94 kg/m^3 with a standard variation of 0.66 kg/m^3 . Due to the extremely low ET in the Indian States of Rajasthan and Madhya Pradesh, water productivity in these areas show higher values despite low yield. These States still cultivate traditional low-yielding wheat varieties which incidentally have high cooking quality and fetch a premium price in the market. The growing season in these States is also shorter due to a shorter winter period and early maturity

of the crop. The high yield areas showed high WP values. The Indian State of Bihar has the largest areas with lowest WP, which means that there is significant scope for improvement in this area. The downstream areas of the Ganges show relatively high WP despite high variability in yield.

The average WP of rice, expressed in terms of US dollars in 2005 at local market price, is $0.121 \text{ US\$/m}^3$, while for wheat it is $0.148 \text{ US\$/m}^3$. The average WP for the rice-wheat rotation system is $0.131 \text{ US\$/m}^3$ (Figure 8). The spatial variation of overall WP of rice-wheat is found to be different both from rice and wheat WP maps. The shared areas of rice and wheat cultivation are influenced by wheat more than rice due to higher WP values of wheat. Some areas have low WP of wheat but high WP of rice, and in some other areas this situation is reversed. The WP of rice contributed 50.7% to the overall WP due to a larger cultivation area despite lower WP values (Figure 8).

Accuracy and Uncertainty Analysis

This section aims to assess the accuracy and analyze uncertainties of the study. As large areas and long time spans are covered, validation is difficult due to data limitations. Table 1 summarizes the comparisons of ET, yield and WP values of rice generated from this study and extracted from other literature. The accuracy of ET, yield and WP are then discussed using both quantitative and qualitative approaches. However,

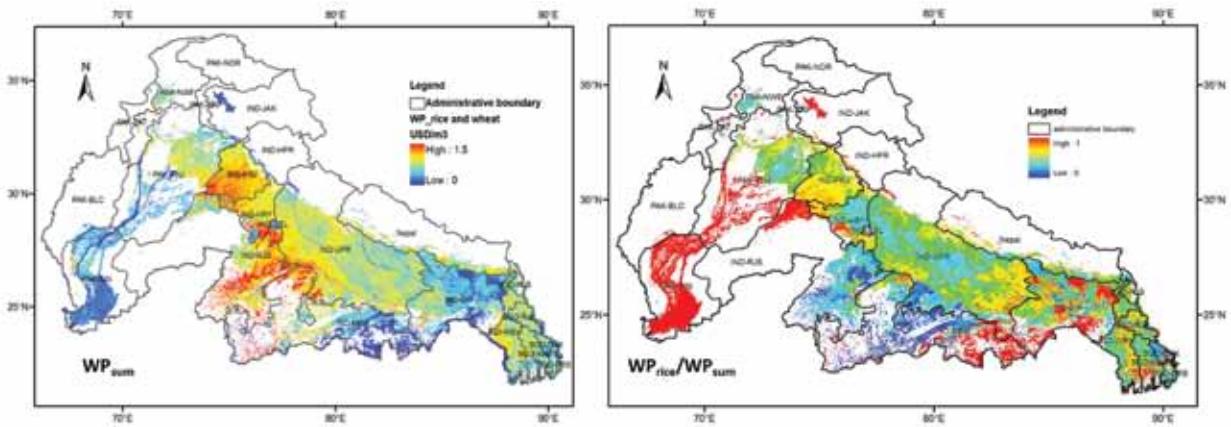


FIGURE 8. Water Productivity of the rice-wheat rotation system in the IGB and the contribution of rice to total WP.

it needs to be noticed that there is a risk of comparing RS results with conventional studies. RS estimate is the average of a pixel which varies from 0.36 ha (Landsat ETM+ thermal) to 100 ha (MODIS thermal) in resolution. To compare these values with modeling or field sampling results, which are often to the point, does not prove good or bad accuracy due to the scale discrepancy. Even when compared with other RS products, one needs to notice the resolution difference, and pay particular attention if the results represent the same meaning.

The yields generally fall in the range given by other literature and agree with field measurements. The exception is the rice yields from this study which are significantly lower in the Indian State of Madhya Pradesh. This is because the yields provided by Mishra et al. (1997) were recorded from controlled field experiments which are relatively high, while statistical values generally show low values but high variation within the State. The estimated yields and the actual yields measured from field campaigns carried out in this study have a coefficient of determination (R^2) at 0.44 (sample size 30). However, it needs to be noticed in this comparison that the MODIS NDVI spatial resolution is 250 m x 250 m, while the measured yield is taken from 1 m x 1 m plots. The MODIS pixel is an average of 62,500 square meters (m^2), which in most cases includes mixed vegetation. This difference in resolution is an important factor to be considered when interpreting results. This will be discussed further

for ET validation. Nevertheless, the overall accuracy of the final yield map is bounded in a satisfactory range because of two reasons. First, the model is a linear extrapolation from district statistical data. Hence, the accuracy depends on the quality of input data taken from statistics which is governed by the officially accepted national standards. Second, possible statistical errors of certain districts cause biases only within the same districts and would not be transferred to other districts.

It is observed that the ET from this study is slightly lower in most cases compared to those extracted from other literature. The reasons for low ET could be attributed to: (a) mixed land cover of each pixel classified as a “pure” crop field, and (b) crop stress. The spatial resolution of the MODIS thermal band used to estimate ET is 1 km x 1 km. In such a big area, rice only grows in a part of it. The rest could be field bunds, trees, barren land and other crops. Depending on the percentage of the rice area, the average ET of the pixel could be as low as 167 mm. A similar trend was also observed from past studies. Bastiaanssen et al. (1999b) used SEBAL to estimate ET of wheat and observed values as low as 180 mm in the Indian State of Haryana. In another effort, Bastiaanssen et al. (2006) and Singh et al. (2006) examined WP of rice for the same area using RS and the Soil-Water-Atmosphere-Plant (SWAP) modeling separately. The ET, yield and WP level using RS are all lower than point SWAP modeling. This study,

TABLE 1. Comparison of ET, yield and water productivity of rice and wheat from this study and extracted from other literature.

Location	Crop	ET (mm)	Yield (t/ha)	Water productivity (kg/m ³)	References
		This study ^b	Literature	This study	Literature
Punjab, India	Rice	534	408-527	6.18	4.6-6.4
			430-579		5.7-8.0
		N/A ^a		N/A ^a	
Northwestern India	Rice	489	N/A ^a	4.92	N/A ^a
			N/A ^a		N/A ^a
Madhya Pradesh, India	Rice	256	N/A ^a	1.28	4.6-6.4
			858-960		7.3-9.0
Sirs, India	Rice	492	500-600	5.0	1.0-5.5
Pindi Bhatian, Pakistan	Rice	472	544 ^b	2.69	2.8-3.7
Indus Basin, Pakistan	Rice	396	220-880	2.72	1.0-4.0
Global	Rice	416	400-850	3.0	2.8-11.0
Haryana, India	Wheat	412	180-450	4.25	4.1
Western IGB	Wheat	366	295-330	3.63	3.2-4.9
IGB	Wheat	299	N/A ^a	2.65	N/A ^a

Notes: ^a the values were not given in the literature.^b WP values given for this study are averages of the Division/State/Basin as the coordinates of WP values from literature are unknown.

which used 1 km MODIS data, has lower ET and WP values than those given by Bastiaanssen et al. (2006), which are based on the fusion of the ETM+ (30 m) and the Advanced Very High Resolution Radiometer (AVHRR) (1.1 km) images. The ground truth data showed a higher percentage of rice areas (more homogenous cropping pattern) in the Indian States of Punjab and Haryana where this study observed the closest ET to the values given in other literature. For the Indian States of Rajasthan and Madhya Pradesh, which have a low percentage of rice areas, this study showed a significantly lower ET. Crop stress is another important constraint. The average rice yield in the IGB is low compared with many other parts of the world. Low yield could be attributed to many constraining factors including crop variety, soil, water and climate which all lead to reduced transpiration. The fact that a large area of rice in the eastern region remains under

rainfed cultivation is a significant factor directly contributing to water stress.

The WP values produced by this study also fall within a reasonable range. They generally agree with values in other literature except in the case of Madhya Pradesh for the same reason of yield differences as explained above. The WP values of rice in the Pakistan portion of the Indus Basin are higher than those given by Waterwatch (2003), which were also based on RS. Further comparison revealed a significantly higher ET by Waterwatch (2003) as a result of an expanded growth stage towards early June, when the pan evaporation was at peak rate. The study by Zwart et al. (2010), also based on RS, was the only one from other literature that covered the whole of the IGB. It developed an innovative approach by using RS exclusively to directly map the WP of wheat which provides very close values to those of this study.

Causes for Variation and Scope for Improvement

Spatial Analysis on Causes for Variation

Large variations in water consumption and water productivity of rice and wheat could be explained by a number of factors; for example, land fertility, water supply, crop management and climatic conditions. This section aims to explore some of the factors affecting water productivity in the basin. The rainfall measured from TRMM, the MODIS land surface temperature, and the ratio of ET_a to ET_p (an indicator of water stress) is compared with each other for rice and wheat (Figure 9). The basin DEM, groundwater depth of the Indian part, and main river streams of the IGB are also included in the comparison.

Total rainfall during the rice growing season is much higher than that of the wheat season, and rainfall in the Indus Basin is lower than that in the Ganges Basin during the rice growing season but

higher during the wheat season. LST variations are similar in both seasons. The highest temperature is observed in the downstream areas of the Indus Basin where deserts dominate the landscape. The lowest temperature occurs in the northern mountain areas. DEM shows, in main agricultural areas, that the landscape is relatively flat. However, the altitude of the southern part of the Ganges Basin is relatively high. The groundwater depth showed an obvious declining trend from east to the west. Large areas in Bihar and West Bengal have very shallow groundwater depth. However, it becomes deep in the Indian States of Punjab and Rajasthan.

Rice performance shows diverse variations in comparison to the constraining factors. The ET_p of rice is lower in the Ganges Basin, which is opposite to rainfall distribution. Significant crop stress (ET_a/ET_p , the lower the value the greater the stress) is observed in large parts of the basin,

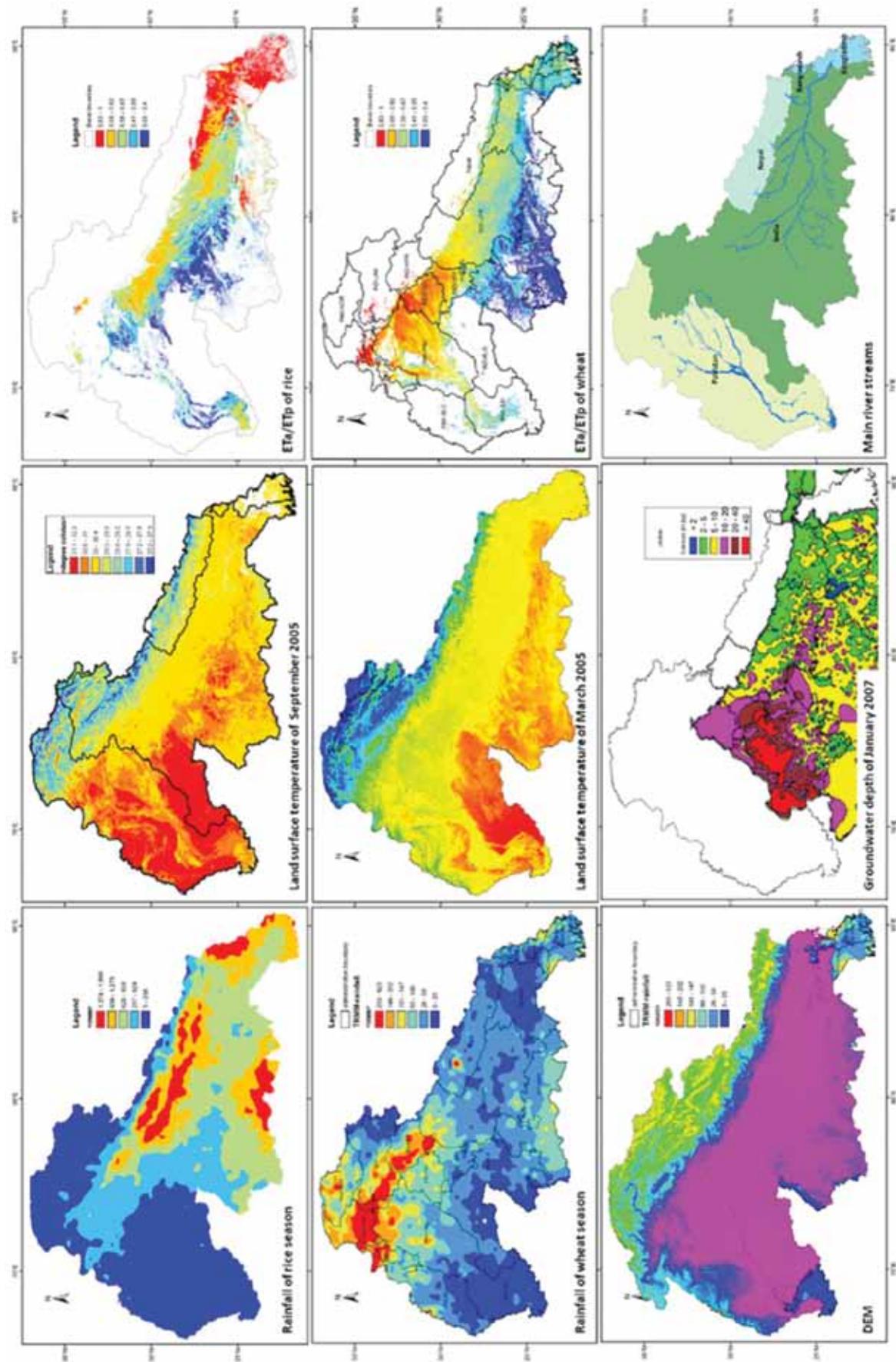


FIGURE 9. Comparison of potential factors contributing to the variation in water productivity of rice and wheat in the IGB.

particularly in the Indus Basin and the southern part of the Ganges Basin. Indus is a closed basin facing severe water scarcity. Parts of the Sind and Punjab provinces in Pakistan, which are close to the bright spots in the Indian State of Punjab, also witnessed significant water stress. The NDVI profiles showed that these areas have complex cropping patterns in comparison to the Indian State of Punjab. The diverse crop types and growing periods could both lead to low average pixel ET. The Indian States of Madhya Pradesh and Rajasthan in the southern part of the Ganges Basin, where the most severe water stress is observed in the rainfed areas, is located in high elevation and warm areas and far from the main river streams. The well-performing Indian State of Punjab showed little water stress in spite of a deep groundwater table and low rainfall due to good irrigation infrastructure.

The ET, yield and water productivity indices of wheat are more consistent across the basin. High ET is accompanied with high yield and high WP. The *Rabi* season is relatively dry and irrigation is the main contributing factor to ET. Wheat yields are more related to irrigation volume but less to rainfall, river flows and soil moisture. This explains the reason for high wheat yields in the Indian States of Haryana and Punjab, and the Punjab Province in Pakistan; extensive irrigation is practiced in these areas, and is accompanied by severe groundwater overexploitation.

A high rate of ET is observed in high rainfall areas, which, however, was not converted into better performance. Rainfall in the downstream of the Ganges is high, which is complemented by higher flow rates in the rivers and shallow groundwater. Better water availability means more water for evapotranspiration. However, it does not necessarily lead to higher yield and water productivity. This could be attributed to poor local crop and water management practices; especially low fertilizer use, use of traditional crop varieties, and crop disease and pests. Rainfall may occur at anytime. Hence, higher rainfall areas have more water to evaporate but could still suffer from water stress during the critical crop growth period (especially the terminal grain filling stage), which drastically affects the final

grain yield accumulation. This is especially true for rice because rice yield and rice water stress (as indicated by ET_a/ET_p) showed contradictory trends. Wheat yield and WP follows more closely the trend of ET. As explained before, wheat yields rely heavily on irrigation. Hence, less non-beneficial water consumption occurs.

Further analysis revealed that weather conditions as reflected by reference ET have no direct link with actual ET. The high elevation zones in the southern part of the Ganges Basin, which is far from the main river streams, have a low ET rate. However, large areas in the flat plains close to the main river streams also show very poor performance. The inconsistency between yield and WP against the affecting factors shows that water availability is a major constraining factor in the Indus Basin and in the southern part of Ganges Basin. The main constraint in the Ganges Basin is, however, not water availability or climate, but the water infrastructures, irrigation and crop management practices (Sharma et al. 2010). Well-developed irrigation and drainage systems together with matching management practices can help to supply water during the dry spell, and drain the excess water from rainfall and shallow groundwater. Other land and crop interventions such as leveling, insects and diseases control, fertilizer and variety are also important factors to be considered along with water management.

Scope for Improvement

Scope for improvement of WP could be assessed in two steps: first, through the comparison of “bright spots” and “hot spots,” and second, through site-specific plant maximum photosynthesis capacity assessment. The second approach involves crop modeling for conjunctive water-fertilizer application and crop genetic innovations. It is the long-term goal for achieving food security of the world. However, while water management in most of the developing world is still at a low level, the first approach provides the greatest chance to improve agricultural performance in the near future.

The “bright spot” of both rice and wheat in the Indian State of Punjab and adjacent areas, with 5% of the rice and wheat cropping area in the basin, has a high WP of 0.190 US\$/m³. If the basin average value of 0.131 US\$/m³ could be increased to the same values, the basin could theoretically save 31% of agricultural water consumption with the same quantity of production or increase 45% of production with same quantum of water. Although this is limited by many constraining factors, a small improvement in WP still has a lot of significance for regional food security.

The levels of WP for rice and wheat in the basin are plotted in Figure 10. Large coefficient of variation (CV) values, 0.44 kg/m³ for rice and

0.70 kg/m³ for wheat, are found. High CV means high variability in crop WP values, indicating significant differences in performance of crop water management. In the IGB, the CV of wheat is much higher than the CV of rice, meaning that water management of wheat is more diverse compared with rice. This is because the rainfall during the wheat growing season is very low, and, hence, the contribution from irrigation is more significant. Increasing the irrigation management levels for wheat is probably more relevant and easier to improve basin WP.

The potential for rice and wheat is different both in terms of magnitude and areas of focus. Figure 11 shows the relation of water productivity to yield and yield to ET_a for rice. It is observed

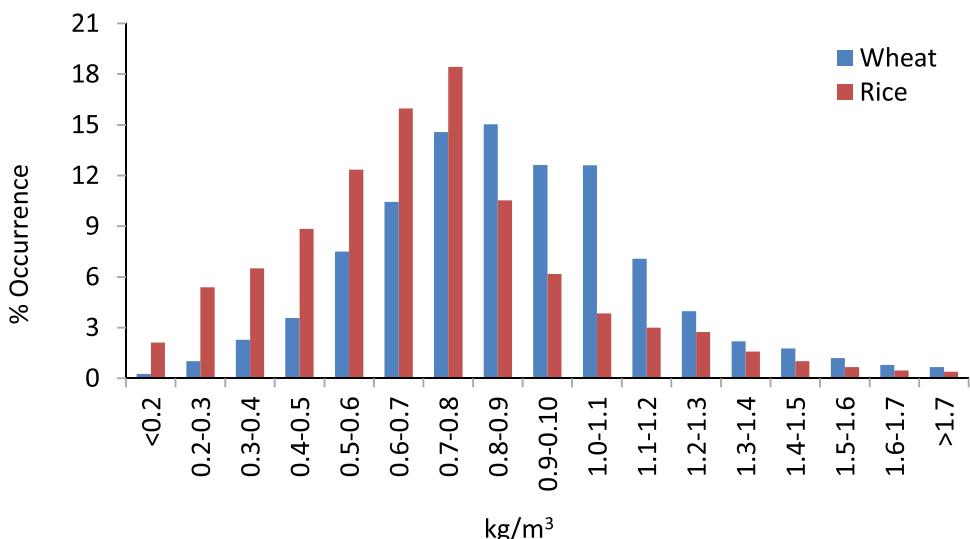


FIGURE 10. The histogram distribution of WP (yield/actual ET) values for rice and wheat.

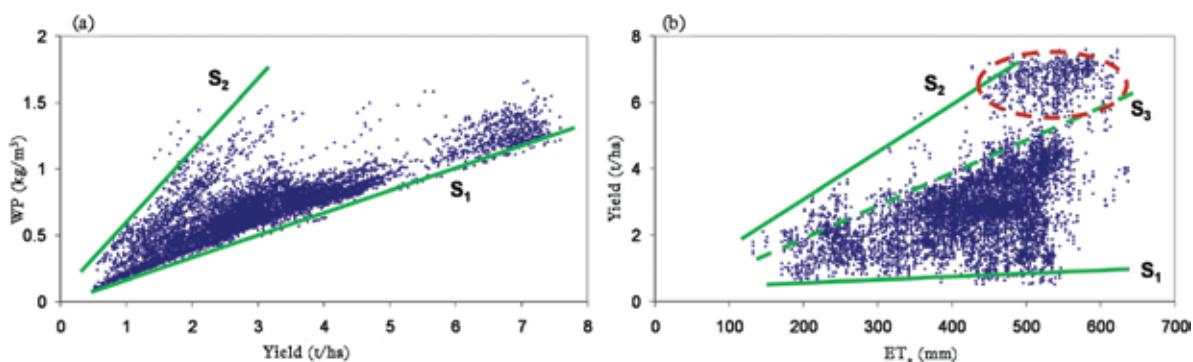


FIGURE 11. Relationship between (a) water productivity and yield, and (b) yield and evapotranspiration of rice (Source: Cai and Sharma 2010).

that water productivity generally increases with an increment of yield (Figure 11(a)), with a relatively lower pace because ET_a too increases with yield. The “bright spot” of the Indian State of Punjab is circled (Figure 11(b)). The yield of this area is so high that it totally changed the slope of yield to ET_a (from S_3 to S_2). Some other areas also have similar ET_a . However, the yield is much lower. The scope for improvement of rice in the region will be to first set a target at the S_2 trend. That is, to improve the yield with similar water consumptions. In this process, the water productivity could be expected to increase 15-25%. The final target would be to increase the yield levels of all areas to the values of the “bright spots”, during the process of which even the “bright spots”

might improve, which could lead to another 10% improvement.

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

Conclusions

Despite intensive agricultural activities, the water productivity in the IGB is relatively low with large variations. While very high water productivity values are observed in some parts (about 5%) of the basin, most areas are still experiencing very low performance. Comparative analysis on crop yield and ET with contributing factors revealed that the physical conditions have less impact on water productivity. Irrigation and on-farm crop management remain as the key elements of success. The crops suffer from water shortage, which exists in large parts of the basin, as well as excess water (waterlogging or flooding) as a result of high rainfall and shallow groundwater in downstream areas of the Ganges Basin.

The successful “bright spots” suggest that appropriate irrigation and drainage infrastructure and matching management practices are the key to sustain high performance. The “bright spot” in the Indian State of Punjab and adjacent areas, with very high WP, is the “model” for other areas. If the basin average WP could be increased to match that of the bright spots with optimal assumption, the basin could theoretically save

31% of agricultural water consumption with the same quantity of production or increase 45% of production with the same quantum of water input. This improvement could be achieved mainly through long-term yield enhancement. In the short term, reducing non-beneficial ET of low-yield areas can also largely contribute to improving WP. However, this needs to be achieved giving full consideration to environmental sustainability. Overexploitation of groundwater resources in northwest India signalled the need for a balanced development.

A data assimilation approach to combine various data sources was introduced in this study. The yield, consumptive use of water and water productivity of the predominant crops, rice and wheat, are determined by combining census, remote sensing, weather and field survey data. The interpolation of yield data from district level to pixel level through NDVI bridges publically accepted official figures and advanced remote sensing technology. The SSEB model is another effort to bring simplicity to crop water consumption studies. The ET method avoids steps to estimate

complex land surface processes and biophysical parameters. As both the yield and ET methods are strongly based on the conventional approach (statistics and FAO reference ET), it does not require field calibration prior to new applications and could easily be applied elsewhere. The accuracy is promising as long as statistical data falls within an acceptable range.

Estimating crop yields and ET to aid agricultural water management using RS have received major development in terms of both methodology and applications over the past decades. However, it still remains a challenge for RS to improve accuracy and strength of estimations for better acceptance by policymakers. Combining RS interpretations with various data

sources could be a potential option to harmonize conflicting results and to enable more in-depth analysis in data-sparse regions. The resolution issue, which is the result of averaging large areas within a single pixel, needs to be considered not only for local, but also for regional applications. This is especially the case for estimation of ET, which often has to use coarse resolution imagery while the actual ET itself is highly variable. Another issue in such kind of spatial mapping is the crop dominance map. A precise crop type map will increase the accuracy of the results. A map that distinguishes major crop varieties will make it even possible to map yield according to each crop variety, which could significantly improve the model accuracy.

References

Ahmad, M. D.; Masih, I.; Turrel, H. 2004. Diagnostic analysis of spatial and temporal variations in crop water productivity: A field scale analysis of the rice-wheat cropping system of Punjab. Pakistan. *Journal of Applied Irrigation Science* 39(1): 43-63.

Allen, R. G.; Pereira, L.; Raes, D.; Smith, M. 1998. *Crop evapotranspiration – Guidelines for computing crop water requirements*. FAO Irrigation and drainage paper 56. Rome, Italy: Food and Agriculture Organization of the United Nations, 290p.

Arino, O.; Gross, D.; Ranera, F.; Bourg, L.; Leroy, M.; Bicheron, P.; Latham, J.; Di Gregorio, A.; Brockman, C.; Witt, R.; Defourny, P.; Vancutsem, C.; Herold, M.; Sambale, J.; Achard, F.; Durieux, L.; Plummer, S.; Weber, J. L. 2007. GlobCover: ESA service for global land cover from MERIS. In: *Proceedings of the International Geoscience and Remote Sensing Symposium (IGARSS), Barcelona (Spain), July 2007*, pp. 2412-2415.

Bastiaanssen, W. G. M.; Molden, D. J.; Thiruvengadachari, S.; Smit, A. M. F. R.; Mutuwatte, L.; Jayasinghe, G. 1999a. *Remote sensing and hydrologic models for performance assessment in Sirsa Irrigation Circle, India*. Colombo, Sri Lanka: International Water Management Institute. (IWMI Research Report 27).

Bastiaanssen, W. G. M.; Thiruvengadachari, T.; Sakthivadivel, R.; Molden, D. J. 1999b. Satellite remote sensing for estimating productivities of land and water. *International Journal of Water Resources Development* 15(1-2): 181-194.

Bastiaanssen, W. G. M.; Ali, S. 2003. A new crop forecasting model based on satellite measurements applied across the Indus Basin, Pakistan. *Agriculture, Ecosystem and Environment* 94: 321-340.

Bastiaanssen, W. G. M.; Zwart, S. J.; Pelgrum, H. 2006. Remote sensing analysis. In: Dam, J. C. van; Malik, R. S. (Eds.), *Water productivity of irrigated crops in Sirsa district, India*. WATPRO final report, Wageningen, pp. 85-96.

Becker-Reshef, I.; Justice, C.; Sullivan, M.; Vermote, E.; Tucker, C.; Anyamba, A.; Small, J.; Pak, E.; Masuoka, E.; Schmaltz, J.; Hansen, M.; Pittman, K.; Birkett, C.; Williams, D.; Reynolds, C.; Doorn, B. 2010. Monitoring global croplands with coarse resolution earth observations: The Global Agriculture Monitoring (GLAM) project. *Remote Sensing* 2: 1589-1609.

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

Cai, X. L.; Cui, Y. L. 2009. Cropping patterns extraction using multi-sensor and multi-temporal remotely sensed data. *Transactions of the Chinese Society of Agricultural Engineering* 25(8): 124-130.

ERDAS (Earth Resources Data Analysis System). 2009. ERDAS Imagine, ERDAS field guide. Atlanta, USA.

Frolking, S.; Qiu, J.; Boles, S.; Xiao, X.; Liu, J.; Zhuang, Y.; Li, C.; Qin, X. 2002. Combining remote sensing and ground census data to develop new maps of the distribution of rice agriculture in China. *Global Biogeochemical Cycles* 16(4): 1-10.

Gowda, P. H.; Senay, G. B.; Colaizzi, P. D.; Howell, T. A. 2008. *Simplified surface energy balance (SSEB) approach for estimating actual ET: An evaluation with lysimeter data*. Paper presented at ASABE Annual International Meeting, Providence, Rhode Island, 2008.

Groten, S. M. E. 1993. NDVI-Crop monitoring and early yield assessment of Burkina Faso, *International Journal of Remote Sensing* 14: 1495–1515.

Hussain, I.; Sakthivadivel, R.; Amarasinghe, U.; Mudasser, M.; Molden, D. 2003. *Land and water productivity of wheat in the western Indo-Gangetic plains of India and Pakistan: A comparative analysis*. Colombo, Sri Lanka: International Water Management Institute. (IWMI Research Report 65).

Khepar, S. D.; Sondhi, S. K.; Kumar, S.; Singh, K. 1997. *Modelling effects of cultural practices on water use in paddy fields – A case study*. Research Bulletin, Publication No. NP/SWE-1, Punjab Agricultural University, Ludhiana, India.

Kijne, J. W.; Barker, R.; Molden, D. 2003. Improving water productivity in Agriculture. In: Kijne, J. W.; Barker, R.; Molden, D. (Eds.), *Water productivity in agriculture: Limits and opportunities for Improvement*. UK: CABI Publishing, pp. xi-xix.

Leff, B.; Ramankutty, N.; Foley, J. A. 2004. Geographic distribution of major crops across the world. *Global Biogeochemical Cycles* 18, GB1009.

Loveland, T. R.; Reed, B. C.; Brown, J. F.; Ohlen, D. O.; Zhu, Z.; Yang, L.; Merchant, J. W. 2000. Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. *International Journal of Remote Sensing* 21: 1303–1330.

Mahajan, G.; Bharaj, T. S.; Timsina, J. 2009. Yield and water productivity of rice as affected by time of transplanting in Punjab, India. *Agricultural Water Management* 96(3): 525–532.

Mishra, H. S.; Rathore, T. R.; Pant, R. C. 1997. Root growth, water potential, and yield of irrigated rice. *Irrigation Science* 17: 69–75.

Molden, D.; Murray-Rust, H.; Sakthivadivel, R. 2003. A water-productivity framework for understanding and action. In: Kijne, J. W.; Barker, R.; Molden, D. (Eds.), *Water productivity in agriculture: limits and opportunities for improvement*. Wallingford, UK: CAB International, pp. 1-18.

Molden, D. 1997. *Accounting for water use and productivity*. SWIM Paper 1. Colombo, Sri Lanka: International Water Management Institute.

Molden, D.; Frenken, K.; Barker, R.; de Fraiture, C.; Mati, B.; Svendsen, M.; Sadoff, C.; Finlayson, C. M. 2007. Trends in water and agricultural development. In: Molden, D. (Ed.), *Water for food, water for life: A comprehensive assessment of water management in agriculture*. London: Earthscan, pp. 57-89.

Oza, S. R.; Panigrahy, S.; Parihar, J. S. 2008. Concurrent use of active and passive microwave remote sensing data for monitoring of rice crop. *International Journal of Applied Earth Observation and Geoinformatics* 10(3): 296-304.

Reynolds, C. A. 2010. Real-time hydrology operations at USDA for monitoring global soil moisture and auditing national crop yield estimates. In: Gebremichael, M.; Hossain, F. (Eds.), *Satellite rainfall applications for surface hydrology*. New York, USA: Springer, pp. 267-293.

Rodell, M.; Velicogna, I.; Famiglietti, J. S. 2009. Satellite-based estimates of groundwater depletion in India. *Nature* 460: 999-1002.

Sadler, E. J.; Bauer, P. J.; Busscher, W. J.; Millen, A. J. 2000. Site-specific analysis of a droughted corn crop: Water use and stress. *Agronomy journal* 92: 403-410.

Sandhu, B. S.; Khera, K. L.; Prihar, S. S.; Singh, B. 1980. Irrigation need and yield of rice on a sandy loam soil as affected by continuous and intermittent submergence. *Indian Journal of Agriculture Science* 50(6): 492-496.

Sakthivadivel, R.; Thiruvengadachari, S.; Amerasinghe, U.; Bastiaanssen, W. G. M.; Molden, D. 1999. *Performance evaluation of the Bhakra irrigation system, India, using remote sensing and GIS techniques*. Colombo, Sri Lanka: International Water Management Institute. (IWMI Research Report 28).

Schmugge, T. J.; Kustas, W. P.; Ritchie, J. C.; Jackson, T. J.; Rango, A. 2002. Remote sensing in hydrology. *Advances in Water Resources* 25: 1367-1385.

Senay, G. B.; Verdin, J. 2003. Characterization of yield reduction in Ethiopia using a GIS based crop water balance model. *Canadian Journal of Remote Sensing* 29(6): 687-692.

Senay, B. G.; Budde, M.; Verdin, J. P.; Melesse, A. M. 2007. A coupled remote sensing and simplified surface energy balance approach to estimate actual evapotranspiration from irrigated fields. *Sensors* 7(6): 979-1000.

Shah, T.; Singh, O. P.; Mukherji, A.; 2006. Groundwater irrigation and South Asian agriculture: Empirical analysis from a large scale survey of India, Pakistan, Nepal and Bangladesh. *Hydrogeology Journal* 14(3): 286-309.

Sharma, B.; Amarasinghe, U.; Sikka, A. 2008. Indo-Gangetic river basins: Summary situation analysis. New Delhi, India: International Water Management Institute. Pp14.

Sharma, B.; Amarasinghe, U.; Cai, X.; de Condappa, D.; Shah, T.; Mukherji, A.; Bharati, L.; Ambili, G.; Qureshi, A.; Pant, D.; Xenarios, S.; Singh, R.; Smakhtin, V. 2010. The Indus and the Ganges: River basins under extreme pressure. *Water International* 35(5): 493-521.

Singh, K. B.; Gajri, P. R.; Arora, V. K. 2001. Modelling the effects of soil and water management practices on the water balance and performance of rice. *Agricultural Water Management* 49: 77-95.

Singh, R.; Dam, J. C. van; Feddes, R. A. 2006. Water productivity analysis of irrigated crops in Sirsa district, India. *Agricultural Water Management* 82(3): 253-278.

Thayyen, R. J.; Gergan, J. T.; Dobhal, D. P. 2005. Slope lapse rates of temperature in Din Gad (Dokriani Glacier) catchment, Garhwal Himalaya, Indian Bulletin of Glaciol. *Research* 22: 31-37.

Thenkabail, P. S.; Biradar, C. M.; Turrall, H.; Noojipady, P.; Li, Y. J.; Vithanage, J.; Dheeravath, V.; Velpuri, M.; Schull, M.; Cai, X. L.; Dutta, R. 2006. *An irrigated area map of the world (1999) derived from remote sensing*. Colombo, Sri Lanka: International Water Management Institute. Pp 74. (IWMI Research Report 105).

Thenkabail, P. S.; Gangadhara Rao, P.; Biggs, T.; Krishna, M.; Turrall, H. 2007. Spectral matching techniques to determine historical land use/land cover (LULC) and irrigated areas using time-series AVHRR pathfinder datasets in the Krishna River Basin, India, *Photogrammetric Engineering and Remote Sensing* 73(9): 1029-1040.

Thiruvengadachari, S.; Sakthivadivel, R. 1997. *Satellite remote sensing for assessment of irrigation system performance: A case study in India*. Colombo, Sri Lanka: International Irrigation Management Institute. 23 pp. (IIMI Research Report 9).

Tuong, T. P.; Bouman, B. A. M. 2003. Rice production in water scarce environments. In: Kijne, J. W.; Barker, R.; Molden, D. (Eds.), *Water productivity in agriculture: Limits and opportunities for improvement*. Wallingford, UK: CAB International. pp. 53-67.

Ullah, M. K.; Habib, Z.; Muhammad, S. 2001. *Spatial distribution of reference and potential evapotranspiration across the Indus Basin Irrigation Systems*. Lahore, Pakistan: International Water Management Institute. (IWMI Working Paper 24).

Waterwatch. 2003. *Crop and water productivity of the Pakistan wheat and rice systems*. Technical Report. Wageningen, the Netherlands.

Xiao, X.; Boles, S.; Froking, S.; Li, C.; Babu, J. Y.; Salas, W.; Moore, B. 2006. Mapping paddy rice agriculture in South and Southeast Asia using multi-temporal MODIS images. *Remote Sensing of Environment* 10: 95–113.

Zwart, S. J.; Bastiaanssen, W. G. M. 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural Water Management* 69(2): 115-133.

Zwart, S. J.; Bastiaanssen, W. G. M.; Fraiture, C.; Molden, D. J. 2010. A global benchmark map of water productivity for rainfed and irrigated wheat. *Agricultural Water Management* 97(10): 1617-1627.

IWMI Research Reports

140 *An Assessment of Crop Water Productivity in the Indus and Ganges River Basins: Current Status and Scope for Improvement.* Xueliang Cai, Bharat R. Sharma, Mir Abdul Matin, Devesh Sharma and Sarath Gunasinghe. 2010.

139 *Shallow Groundwater in the Atankwidi Catchment of the White Volta Basin: Current Status and Future Sustainability.* Boubacar Barry, Benony Kortatsi, Gerald Forkuor, Murali Krishna Gumma, Regassa Namara, Lisa-Maria Rebelo, Joost van den Berg and Wolfram Laube. 2010.

138 *Bailout with White Revolution or Sink Deeper? Groundwater Depletion and Impacts in the Moga District of Punjab, India.* Upali A. Amarasinghe, Vladimir Smakhtin, Bharat R. Sharma and Nishadi Eriyagama. 2010.

137 *Wetlands, Agriculture and Poverty Reduction.* Matthew McCartney, Lisa-Maria Rebelo, Sonali Senaratna Sellamuttu and Sanjiv de Silva. 2010.

136 *Climate Change, Water and Agriculture in the Greater Mekong Subregion.* Robyn Johnston, Guillaume Lacombe, Chu Thai Hoanh, Andrew Noble, Paul Pavelic, Vladimir Smakhtin, Diana Suhardiman, Kam Suan Pheng and Choo Poh Sze. 2010.

135 *Impacts of Climate Change on Water Resources and Agriculture in Sri Lanka: A Review and Preliminary Vulnerability Mapping.* Nishadi Eriyagama, Vladimir Smakhtin, Lalith Chandrapala and Karin Fernando. 2010.

134 *Evaluation of Current and Future Water Resources Development in the Lake Tana Basin, Ethiopia.* Matthew McCartney, Tadesse Alemayehu, Abeyu Shiferaw and Seleshi Bekele Awulachew. 2010.

133 *Mapping Drought Patterns and Impacts: A Global Perspective.* Nishadi Eriyagama, Vladimir Smakhtin and Nilantha Gamage. 2009.

132 *Malaria Transmission in the Vicinity of Impounded Water: Evidence from the Koka Reservoir, Ethiopia.* Solomon Kibret, Matthew McCartney, Jonathan Lautze and Gayathree Jayasinghe. 2009.

131 *Implementing Integrated River Basin Management: Lessons from the Red River Basin, Vietnam.* François Molle and Chu Thai Hoanh. 2009.

130 *Economic Gains of Improving Soil Fertility and Water Holding Capacity with Clay Application: The Impact of Soil Remediation Research in Northeast Thailand.* Rathinasamy Maria Saleth, Arlene Inocencio, Andrew Noble and Sawaeng Ruaysoongnern. 2009.

Electronic copies of IWMI's publications are available for free.

Visit

www.iwmi.org/publications/index.aspx

Related Publications

Cook, S.; Gichuki, F.; Turrel, H. 2006. ***Agricultural water productivity: Estimation at plot, farm and basin scale***. Colombo, Sri Lanka: International Water Management Institute (IWMI). Challenge Program Secretariat. 16p. (CGIAR Challenge Program on Water and Food (CPWF), Basin Focal Project Working Paper 2)

<http://publications.iwmi.org/pdf/H039742.pdf>

Hussain, I.; Sakthivadivel, R.; Amarasinghe, U.; Mudasser, M.; Molden, D. 2003. ***Land and water productivity of wheat in the western Indo-Gangetic Plains of India and Pakistan: A comparative analysis***. Colombo, Sri Lanka: International Water Management Institute (IWMI). 56p. (IWMI Research Report 065)

www.iwmi.org/Publications/IWMI_Research_Reports/PDF/pub065/Report65.pdf

Kijne, J. W.; Barker, R.; Molden, D. (Eds.). 2003. ***Water productivity in agriculture: limits and opportunities for improvement***. Wallingford, UK: CABI; Colombo, Sri Lanka: International Water Management Institute (IWMI). 332p. (Comprehensive Assessment of Water Management in Agriculture Series 1)

www.iwmi.org/Publications/CABI_Publications/CA_CABI_Series/Water_Productivity/Unprotected/0851996698toc.htm

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 (IWMI). 152p.

www.iwmi.org/Publications/Other/PDF/NRLP_series_4-final_Rev.pdf

Wani, S. P.; Rockström, J.; Oweis, T. (Eds.). 2009. ***Rainfed agriculture: Unlocking the potential***. Wallingford, UK: CABI; Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT); Colombo, Sri Lanka: International Water Management Institute (IWMI). 310p. (Comprehensive Assessment of Water Management in Agriculture Series 7).

www.iwmi.org/Publications/CABI_Publications/CA_CABI_Series/Rainfed_Agriculture/Protected/Rainfed_Agriculture_Unlocking_the_Potential.pdf

Postal Address

P O Box 2075
Colombo
Sri Lanka

Location

127 Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Telephone

+94-11-2880000

Fax

+94-11-2786854

E-mail

iwmi@cgiar.org

Website

www.iwmi.org