Diagnostic analysis of spatial and temporal variations in crop water productivity: A field scale analysis of the rice-wheat cropping system of Punjab, Pakistan

M. D. Ahmad, I. Masih and H. Turral

2004

First published in:

Journal of Applied Irrigation Science, Vol. 39. No 1/2004, pp. 43 - 63
ISSN 0049-8602

This electronic version of the publication has been supplied for personal use only.

personal copy

Zeitschrift für Bewässerungswirtschaft, 39. Jahrg., Heft 1 /2004, ISSN 0049-8602 **Seiten 43 - 63**

Diagnostic analysis of spatial and temporal variations in crop water productivity: A field scale analysis of the rice-wheat cropping system of Punjab, Pakistan

Analyse räumlicher und zeitlicher Variationen der Wasserproduktivität von landwirtschaftlichen Kulturen: Eine Analyse auf Feldebene von Reis-Weizen-Anbausystemen im Punjap, Pakistan

M. D. Ahmad, I. Masih
and H. Turral

Stichworte
Wasserproduktivität; Wasserbilanz; Wassermanagement; Modellierung auf Feldebene; Reis-Weizen-Anbausystem; Pakistan
Keywords
Water productivity; water balance; water management; field scale modeling, rice-wheat system, Pakistan.

Zusammenfassung
Das Reis-Weizen-Anbausystem ist die wichtigste Quelle der Nahrungsmittelproduktion in der Welt. Um die künftige Nachfrage nach Nahrungsmitteln befriedigen zu können, bedarf die Wasserproduktivität dieses Anbausystems erheblicher Verbesserungen. Dies insbesondere da Wasser knapper und die Konkurrenz um die Wasserressourcen zwischen der Landwirtschaft und den anderen Wassernutzungssektoren ständig zunimmt. Die vorliegende Arbeiten berichtet über die Ergebnisse einer Studie, in der die Wasserproduktivität von Reis und Weizen in einer Systemperspektive analysiert wurde. Hierzu diente das Reis-Weizen-Anbausystem im Punjap, Pakistan als Fallstudie. Die Wasserbilanz und Wasserproduktivität auf Feldebene wurde evaluiert, und zwar unter Verwendung von Messdaten, die auf Feldern von Bauern gewonnen wurden, Simulationsmodellierung und eines umfangreichen Katalogs von Wasserproduktivitäts-Indikatoren. Die Faktoren, die die zeitliche und räumliche Variationen der Wasserproduktivität bedingen, wurden identifiziert und der Umfang der Steigerung der Nahrungsmittelproduktion im Verhältnis zur Verbesserung der Wasserproduktivität diskutiert.

Die durchgeführte Analyse macht deutlich, dass die Landwirte dazu tendieren die Nahrungsmittelproduktion und die Deckungsbeiträge je Nutzflächeneinheit auf Kosten der Wasserproduktivität zu steigern. Um die Wasserproduktivität auf einem bestimmten Niveau zu halten und/oder sie zu erhöhen bedarf das Management der nicht kontrollierbaren Faktoren (z.B. klimatische Variabilität) zusammen mit der Verbesserung der kontrollierbaren Faktoren (ackerbauliche Praktiken, On-farm water management) einer sorgfältigen Planung und entsprechender Maßnahmen. Die Wassserbilanz- und Wasserproduktivitäts-Indikatoren können bei räumlichen und zeitlichen Analysen hilfreich sein bei der Bewertung von Bewässerungskulturen und bei der Entwicklung von Strategien zur Verbesserung der Nahrungsmittelproduktion und der Wasserproduktivität.

Abstract

The rice-wheat cropping system is the most important source of food production for the world. To meet future demands, water productivity in this cropping system needs considerable improvement as water is becoming scarcer and competition among agriculture and other sectors is increasing. This paper studies the water productivity of rice and wheat in a system perspective by taking rice-wheat cropping system of Pakistan's Punjab as a case study. Field scale water balance and water productivity is evaluated using measured data from the farmers' field, simulation modeling and comprehensive set of water productivity indicators. The factors causing temporal and spatial variations in crop water productivity are identified and scope to enhance food production via improving water productivity is discussed. The study indicates that water productivity per unit of gross inflow ranged from 0.17 to 0.38 Kg/m^3 for rice and 0.78 to 2.03 Kg/m^3 for wheat. The economic water productivity measured in terms of gross margins per unit of gross inflow for rice, wheat and rice-wheat rotation ranged from 5 to 51 $/"000" m^3, 50 to 150 $/ "000" m^3 and 26 to 76 $/ "000" m^3, respectively. Irrigation water productivity was higher than that of gross inflow and the difference was due to the proportion of rainfall in gross water input. The water productivity of rice was lower than wheat when measured in terms gross inflow, irrigation inflow and evapotranspiration. However, in terms of transpiration rice showed almost same physical water productivity as that of wheat. The water productivity varied both spatially and temporally. For sample areas, the spatial variability was mainly due to difference in water use, sowing dates, fertilizer use, soil quality and socio-economic conditions. Rainfall, amount and timing, emerged as the most important factor inducing temporal changes. Water productivity of both rice and wheat showed a decline during the period of investigation. The analysis reveals that the farmers tend to increase their food production, and gross margins per unit of land at the cost of decreased water productivity. To sustain and/or enhance water productivity, the management of uncontrollable factors such as climatic variability along with the improvements in controllable factors such as agronomic and water management practices need careful planning and actions. The application of a comprehensive set of water balance and water productivity indicators for spatial and temporal analysis could help in performance evaluation of irrigated crops and devising strategies for improving food production and water productivity.

1. Introduction

Rice and wheat are the two main cereal crops, which play central role in the human food chain. In Indo-Gangetic plain (IGP) of south Asia, the two crops are the staple food of 1.3 billion people providing 60-94 percent of the calorie intake (TIMSINA and CONNOR, 2001). They are grown in a continuous rotation on about 14 million hectares (Mha) areas of IGP, consisting of Indus (areas in Pakistan, and parts of Punjab and Haryana in India) and the Gangetic Plains (UP, Bihar, and West Bengal in India, Nepal and Bangladesh). The Green Revolution of 1960s saw major increase in the productivity of cereal crops. The production of rice increased from 47 million tons in 1950-52 to 161.5 million tons during 1996-98 in South Asia. Wheat production increased from 9.8 to 85.8 million tons over the same period of time (PINGALI and SHAH, 1999). The major contributory factors in the initial success of the Green Revolution and the

emergence of the rice-wheat system as an important source of food supply were: infrastructure investments; especially surface irrigation system and groundwater development, introduction of the high yielding semi-dwarf varieties of rice and wheat (modern germplasm); political commitment and policy support.

The rapid rise in grain production was initially sustained through the increased input use, horizontal expansion of cultivated area and intensification of land use. But the productivity growth has shown declining trends particularly in intensified rice-wheat systems of Asia over the past two decades (CASSMAN and PINGALI, 1995). The most common threats to the sustainability of such agricultural system are: build up of salinity and waterlogging; depletion and pollution of water resources; changes in soil nutrient status, nutrient deficiencies and evidences of soil toxicities; increased pest build ups, pest related yield losses and associated consequences of increased pesticide use (PINGALI and SHAH, 1999).

Growing water scarcity has further constrained the attainment of goals of food security and sustainable natural resource management. The irrigation sector will have less water in future as competition and demands from the domestic, industrial and environmental sectors keeps on increasing. The challenge for irrigated agriculture will be to produce more food with less water (GUERRA et al., 1998). The worsening situation can only be reverted if water is managed more efficiently and judiciously.

Water accounting and water productivity concepts are useful to evaluate the existing performance and to explore options for real water saving from field to basin scale (MOLDEN, 1997). These concepts require complete understanding of the exiting water use pattern and the interaction of different water balance components, which are complex, at different spatial and temporal scales. This study was carried out with the specific objectives to diagnose the spatial and temporal variations of water productivity for rice and wheat crops in Punjab Pakistan. Diagnostic analysis will provide a picture of existing water use pattern and initial insight whether the water is being used optimally, or there is a scope for water saving and increasing economic efficiency.

2. Materials and methods

2.1 Water productivity

Productivity, in general, is a ratio referring to the unit of output per unit of input. The term water productivity is defined as *the physical mass of production or the economic value of production measured against gross inflows, net inflow, depleted water, process depleted water, or available water* (MOLDEN, 1997; MOLDEN and SAKTHIVADIVAL, 1999).

The expression is most often given in terms of mass of produce, or monetary value, per unit of water. Depending on how the terms in the numerator and denominator

are expressed, water productivity can be expressed in general physical or economic terms. In this study, following physical and economic water productivity indicators were used (Table 1).

Table 1:
Indicators of physical and economic water productivity

Physical (kg/m^3)	Economic ($/m^3$)	
$WP_{Y_Ig} = Y / I_g$	$WP_{GVP_Ig} = GVP / I_g$	$WP_{GM_Ig} = GM / I_g$
$WP_{Y_Irr} = Y / I_{rr}$	$WP_{GVP_Irr} = GVP / I_{rr}$	$WP_{GM_Irr} = GM / I_{rr}$
$WP_{Y_ETa} = Y / ET_a$	$WP_{GVP_ETa} = GVP / ET_a$	$WP_{GM_ETa} = GM / ET_a$
$WP_{Y_Ta} = Y / T_a$	$WP_{GVP_Ta} = GVP / T_a$	$WP_{GM_Ta} = GM / T_a$

[WP : Water Productivity; Y : Yield; GVP: Gross Value of Production; GM: Gross Margin; I_g : Gross Inflow; ET_a : Actual Evapotranspiration; T_a : Actual Transpiration]

2.2 Description of the study area

The rice-wheat production system of Pakistan occupies about 2.2 Mha of the total farmland (21 Mha) of the country and is distributed over various Agro-Ecological Regions of Pakistan (ASLAM et al., 2002). These areas have been categorized into four rice-wheat growing zones based on climate, land use and water use i.e., Zone 1 (Northern Zone): Rice is grown in mountain environment having high rainfall and relatively cold temperature; Zone 2 (Punjab Rice-Wheat Zone): Subtropical Northern Irrigated Plains; Zone 3 (Upper Sindh Zone): Southern irrigated plains. High temperature region; Zone 4 (Lower Sindh Zone): Southern plains and Indus delta Tropical Region (Figure 1).

This study was conducted in Punjab Rice-Wheat Zone (Zone 2). The area comes under the administrative divisions of Gujranwala and Lahore. The canals supplying surface water to these areas are Lower Chenab Canal, Upper Chenab, Marala Ravi, and Central Bari Doab. Groundwater has been extensively developed over the past 40 years by public sector (during initial phase of green revolution) and private sector after 1980s. Today the cropping intensities are more than 150 percent and are higher than the other areas of the Punjab Province.

The climate of the rice-wheat zone of Punjab is semi-arid and typically represents low-lying interior of the Indo-Pakistan sub-continent. Rainfall and temperature shows large seasonal fluctuations. The summer is long and hot, lasting from April through September, with maximum temperature ranging from 21°C and 49°C. Winter lasts from December through February, with maximum air temperature ranging from 25°C to 27°C during day and sometime falling below zero at night. The monsoon elapses from June to September and accounts for about 75% of annual rainfall. There are two distinct cropping seasons: *kharif* (summer) and *rabi* (winter). Rice is cultivated in kharif and wheat in *rabi*. The soil texture is predominantly moderately fine to medium in Punjab rice-wheat zone.

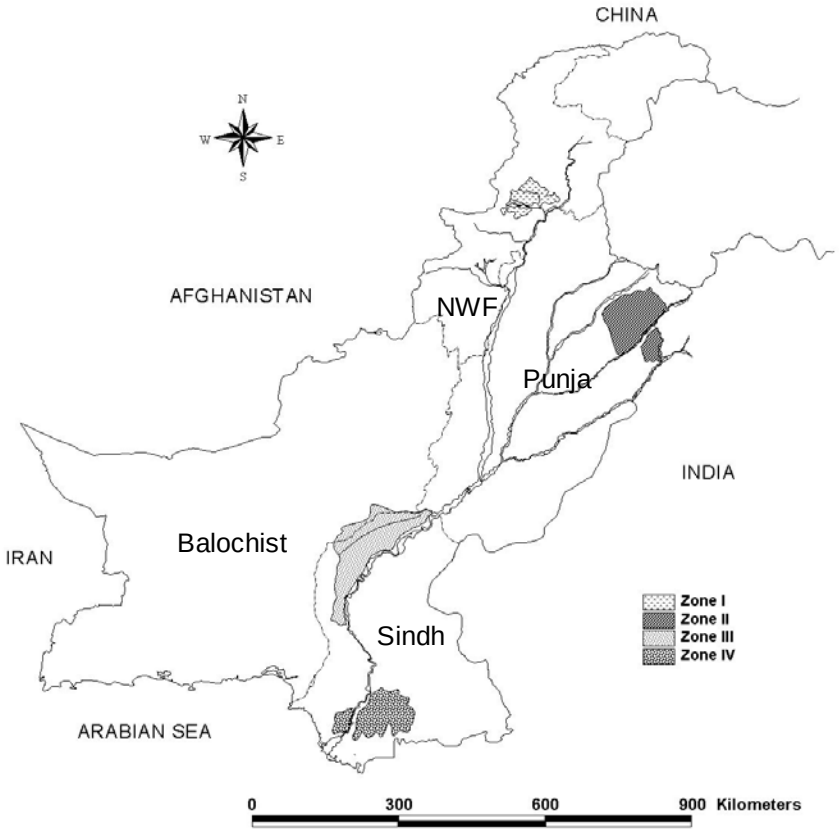

Figure 1:
Location of Rice-wheat cropping zones of Pakistan

2.3 Data collection and analysis

For water productivity analysis two data sets were collected and used from 11 fields selected from the five sample watercourses from rice-wheat system in Rechna Doab (the land between river Ravi and Chenab), Pakistan. The first dataset was obtained from one experimental field for detailed modeling study, while the second dataset, with relatively less detail, was collected from ten farmers' fields.

The *first dataset* was collected from the experimental field of Soil Salinity Research Institute (SSRI), Pindi Bhattian located in the head reach of the LCC west near to the northeastern boarder of Rechna Doab. This field was of 0.42 ha and under rice-wheat rotation. Field data on various water balance and agronomic practices was monitored for two growing seasons, *kharif* 2000 and *rabi* 2000-1. The summary of collected

data, methodology and frequency is given in Table 2. Bowen ratio towers for measuring the actual evapotranspiration rates (ET_a) were installed and operated between June 21 (2000) and March 21 (2001). A physically based numerical model SWAP, Soil-Water-Atmosphere-Plant (van DAM et al., 1997) was applied to understand the transient interaction between different water balance components. SWAP model was calibrated and verified with in situ measurements of soil moisture content and evapotranspiration fluxes (AHMAD et al., 2002). This was the first attempt in Pakistan to verify the unsaturated zone model SWAP using the Bowen ratio technique. The root mean square errors (RMSE) between measured and computed soil moisture content was 0.03 $cm^3 cm^{-3}$. The RMSE for actual evapotranspiration was 0.9 mm d^1, which is a difference of approximately 15% at an evapotranspiration rate of 6 mm d^{-1}. The difference between measured and computed accumulated annual evapotranspiration was much smaller (3%).

Table 2:
Field Data collection for water balance and water productivity analysis (After AHMAD et al., 2002)

Parameter	Collection Method/Instrument	Frequency
Air Temperature	Thermocouple	5 min
Relative Humidity	Thermocouple	5 min
Shortwave Radiation	Pyranometer	5 min
Precipitation	Tipping bucket	30 min
Wind speed	Anemometer	5 min
Phreatic Surface	Piezometeric level (using sounding device and *Diver*)	Daily
Soil moisture content	Frequency domain technique	Weekly
Irrigation	Cut-throat flume & current meter	Event wise
Crop calendar	Field surveys	Continuous
Crop yield	Crop cuttings	Harvest

The *second data* set was collected from 10 farmers' fields distributed to the four different watercourse command areas for two rice (*kharif* 2001 and *kharif* 2002) and two wheat seasons (*rabi* 2001-2 and *rabi* 2002-3). The irrigations applied to these fields were measured by cut-throat flume. Rainfall data was collected from rain gauges installed in the sample areas. Daily temperature, evaporation and rainfall data were also gathered from a nearby meteorological station. Potential crop water requirement (ET_p) was estimated by using Hargreave's equation (ALLEN et al., 1998) and suitable

crop coefficients for the area (PARC, 1982). The daily variation in reference crop evapotranspiration (ET_o) for the study area is shown in Figure 2. Piezometers were installed to monitor groundwater table depth on weekly basis using sounding devices (electric groundwater table recorder). Water ponding in the rice fields was measured on daily basis by the permanently installed gauges in the sample fields. The data regarding soils, crop yields and various agronomic activities such as sowing and harvesting dates, tillage operations, fertilizer and pesticide use was obtained by crop cutting experiments in the farmer fields. The summary of water balance, agronomic practices and yield data for rice and wheat crops is given in Table 3.

Figure 2:
Daily variations in reference evapotranspiration during cropping year 2001-2 in the study area

3. Results and discussion

3.1 Field scale modeling

A comprehensive analysis was done for year 2000-1, through detailed field measurements and SWAP modeling, to compute seasonal and annual water balance and water productivity of rice-wheat system using first dataset (Table 4). The results indicate that irrigation constituted the major portion of the gross inflow for meeting crop water demand compared to rainfall. Irrigation's share in gross inflow was 78 percent (650 mm) and 89 percent (262 mm) for rice and wheat crops respectively. A crop wise comparison shows that rice received about 60 percent more irrigation water than wheat. The gross inflow to rice (837 mm) was 54 % higher than the actual crop evapotranspiration (544 mm). Consequently, a greater amount of water (37 % or

307 mm) percolated to groundwater aquifer. The water balance analysis for wheat showed that the gross inflow (296 mm) was lower than the actual evapotranspiration (314 mm). This deficit was met by water extracted through capillary rise and soil moisture storage, as evident from negative change in storage. Looking from a system perspective for rice and wheat crops, the annual gross inflow was 1133 mm against the actual evapotranspiration of 890 mm. It is pertinent to note that the net transpiration for rice (272 mm in 123 days) was lower than that of wheat (314 mm in 170 days) despite of higher evapotranspiration rates. This shows that about two-third of available water was not actually consumed as transpiration by rice. Similar evidences were found by Jalota and Arora (2002) on similar agro-climatic conditions and soils in Indian Punjab.

Table 3:
Summary of agronomic practices, water input and yields (average values) for rice and wheat, for sample farmer fields, dataset 2, in rice-wheat zone of Punjab, Pakistan

Parameter	Rice		Wheat	
	kharif 2001	*kharif* 2002	*rabi* 2001-2	*rabi* 2002-3
Average field size (ha)	0.24	0.24	0.24	0.24
Number of plowing	4	5	2	2
Number of planking	2	2	2	2
Sowing dates	7/14/2001 to 8/1/2001	7/4/2002 to 8/16/2002	11/12/2001 to 11/24/2001	11/10/2002 to 11/21/2002
Harvesting dates	11/2/2001 to 11/20/2001	11/2/2002 to 11/8/2002	4/20/2002 to 5/4/2002	4/21/2003 to 5/6/2003
Nitrogen (Kg/ha)	173	176	133	150
Total Irrigation (mm)	1051	1640	262	165
Gross rainfall (mm)	282	113	32	178
Gross inflow (mm)	1337	1750	294	343
Yield (Kg/ha)	3535	3702	4521	4424

SWAP modeling result provides a unique opportunity to compute physical and economic water productivity in terms of gross inflow, gross irrigation, actual evapotranspiration and actual transpiration (Table 4).

Table 4:
Summary of field scale water balance and water productivity for rice-wheat area at Pindi Bhattian for kharif 2000 and rabi 2000-01

Parameters/Indicators	Rice	Wheat	Rice-Wheat
Crop duration (days)	123 (June 30 to Oct. 31, 2000)	170 (Nov. 9 - Apr. 28, 2001)	Crop duration (days)
Water Balance Analysis			
Inflow; measured (mm)			
Gross rainfall (R)	187	34	221
Irrigation (I_{rr})	650	262	912
Gross Inflow ($I_g = I_{rr} + R$)	837	296	1133
Outflow; simulated using SWAP (mm)			
Actual evaporation (E_a)	272	32	304
Actual transpiration (T_a)	272	314	586
Actual evapotranspiration (ET_a)	544	346	890
Rainfall Interception (R_i)	4	6	10
Bottom flux (q_{bot})	307	43	350
Storage change (ΔW)	- 19	- 98	- 117
Land Productivity			
Yield (Kg/ha)	2794	3146	
Gross value ($/ha)	464	407	871
Gross margins ($/ha)	193	175	368
Water Productivity			
Physical terms (Kg/m^3)	0.33	1.06	
WP_{Y_Ig}	0.43	1.20	
WP_{Y_Irr}	0.51	0.91	
WP_{Y_ETa}	1.03	1.00	
WP_{Y_Ta}			
Economic terms ($/m^3)			
WP_{GVP_Ig}	0.06	0.14	0.08
WP_{GVP_Irr}	0.07	0.16	0.10
WP_{GVP_ETa}	0.09	0.12	0.10
WP_{GVP_Ta}	0.17	0.13	0.15
WP_{GM_Ig}	0.02	0.06	0.03
WP_{GM_Irr}	0.03	0.06	0.04
WP_{GM_ETa}	0.04	0.05	0.04
WP_{GM_Ta}	0.07	0.06	0.06

(GVP = Gross value of Production, GM = Gross Margins or Net income)

The land productivity for rice and wheat crop was 2794 Kg/ha and 3146 Kg/ha respectively. In physical terms the yield per unit of land for wheat was higher than rice but opposite was true in terms of gross value of production. Rice (*Basmati; fine*

varieties) having the higher market value had gross value of production of 464 $/ha compared 407 $/ha for wheat. Also gross margins per unit of land were higher for rice compared to wheat.

For rice and wheat WP_{Y_Ig} was 0.33 Kg/m^3 and 1.06 Kg/m^3 respectively for cropping year 2001-2. WP_{GVP_Ig} was also higher for wheat (0.14 $/m^3) as compared to rice (0.06 $/m^3). On annual basis this is equivalent to 0.08 $/m^3 for rice-wheat rotation. WP_{GM_Ig} for rice, wheat and rice-wheat rotation was estimated as 0.02, 0.06 and 0.03 $/m^3 respectively. The reason for lower gross margins per unit of water for rice was mainly associated to higher pumpage cost for groundwater withdrawal for irrigation.

The physical and economic water productivities estimated on the basis of irrigation water showed similar trends to those of water productivity per unit of gross inflow (Table 4). The higher values of water productivity measured against irrigation compared to that of gross inflow were mainly influenced by the proportion of rainfall in the gross inflow.

WP_{Y_ETa} was estimated as 0.51 Kg/m^3 and 0.91 Kg/m^3 for rice and wheat crops respectively. This difference in water productivity was negligible when measured in terms of transpiration (both crops showed WP_{Y_Ta} = 1.0 Kg/m^3) and this was the point where WP_{GVP_Ta} and WP_{GM_Ta} of rice exceeded wheat (Table 4). The water productivity of rice is mostly considered lower than wheat, which is often true when not measured in terms of transpiration. Transpiration is the process depletion (i.e. beneficial use) by the crop, while rest of the available water goes to the various other processes such as evaporation (non-process depletion), seepage and percolation. These water components are most often termed as losses, which is not be true when looking in river basin perspective, if water is reused within the same area or downstream (SECKLER, 1996). For instance, in irrigated systems like that of Pakistan's Punjab and many other river basins of the world, this water is often recycled via groundwater abstraction in the similar area or other downstream areas of the river basin (AHMAD, 2002, BASTIAANSSEN et al., 2003). Although this paper only focuses field scale analysis, it is important to note that while studying the water use efficiency and water productivity of the crops the scale considerations should be duly demarcated. The field scale water productivity of rice could be enhanced by minimizing the evaporation losses and seepage and percolation flows by practicing alternate wet/dry irrigation, wet seeded and dry seeded rice (BHUIYAN et al., 1995, TUONG, 1999, HOEK et al., 2001, TABBAL et al., 2002).

3.2 Spatial distribution of water productivity

To study the spatial trends of water productivity *second dataset* was used. Water productivity was computed using physical yield, gross value of production and gross margins against gross inflows and irrigation inflows actually measured at farmers' field. Although it is more useful to compare water productivity against actual transpiration (beneficial use of water by crop) or ET_a, but due to financial

constraints, it was not possible to install sophisticated instruments for ET_a and soil moisture measurement at numerous farmers' fields. Such datasets are essential to properly calibrated and validate hydrological models at field scale. Therefore, in following results water productivity in terms of ET_a and T_a is not discussed.

The physical water productivity of rice and wheat fields located at different watercourse command areas for cropping year 2001-2 is shown by Figure 3. For rice, average WP_{Y_Ig} was estimated as 0.27 Kg/m^3 ranging from 0.18 to 0.42 Kg/m^3. The average WP_{Y_Irr} of rice was about 25 % higher than that of WP_{Y_Ig}. For wheat, the WP_{Y_Ig} was 1.60 Kg/m^3 ranging from 1.00 to 2.00 Kg/m^3. The analysis showed that water productivity varied significantly with respect to location for both rice and wheat crops.

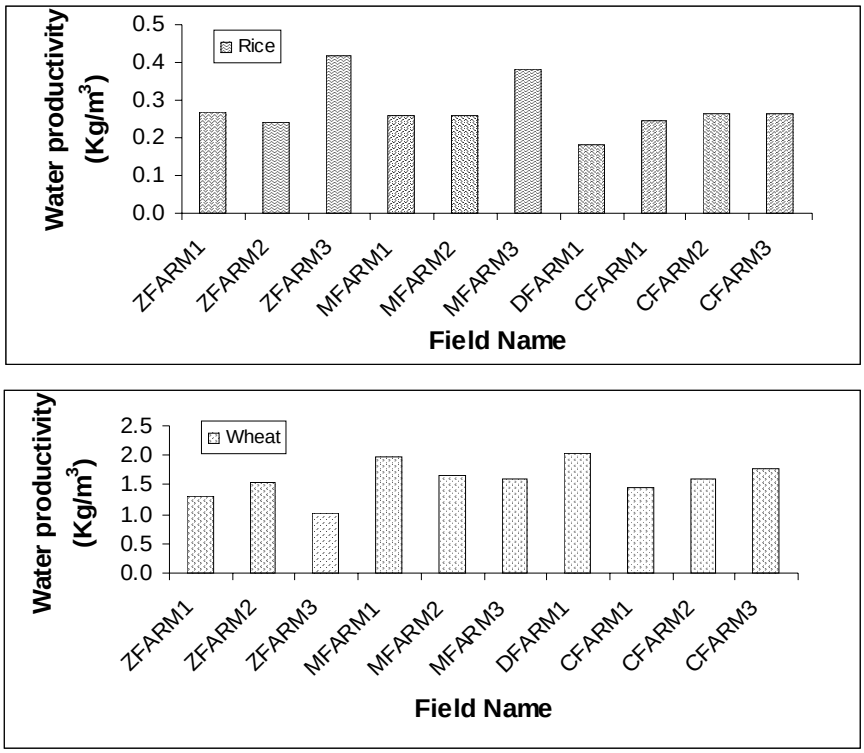

Figure 3:
Spatial distribution of water productivity across selected fields in rice-wheat zone of Punjab, Pakistan

These spatial variations, under similar agro-climatic condition, were mainly attributed to access to irrigation water, soils, groundwater table and quality, farm management, and farmers' socio-economic conditions. The in-depth analysis of the field data and comprehensive survey of the sample fields revealed that access to good quality groundwater was the main contributor in sustaining the crop production. It is worth noting that groundwater contribution approached two-thirds of gross inflow. Where environmental quality was poor (saline soils, and marginal groundwater quality), the crop yield and water productivity were lower. For rice, late sowing, lower fertilizer applications and improper irrigation water use (under irrigation or over irrigation) were the main factors affecting the land and water productivity. For wheat, water productivity showed large variation despite of similar sowing dates, tillage practices, fertilizer and pesticides use, and more noticeably comparable yields. Better conjunctive use of irrigation and rainfall was the main factor where higher water productivity was achieved.

The results of experiments conducted at various locations in Pakistan also show similar evidence in spatial variability in water productivity. The results of the series of experiments conducted by Pakistan Agricultural Research Council (PARC, 1982) showed that the water productivity of wheat (yield per unit of evapotranspiration) ranged from 0.4 Kg/m^3 to 1.2 Kg/m^3 at various experimental locations (Lahore, Bhalwal, Islamabad, Faisalabad, and Peshawar). The variation in water productivity with respect to geographical location was quite noticeable from these experimental results despite similar amounts of fertilizer applications. Table 5 shows a broader picture of water productivity of rice and wheat estimated at field scale in different countries of the world. The water productivity per unit of evapotranspiration for typical lowland rice ranged from 0.4 to 1.6 Kg/m^3 and water productivity per unit of gross inflow varied from 0.20 to 1.1 Kg/m^3. The corresponding values for wheat ranged from 0.65 to 2.0 Kg/m^3 and 0.79 to 1.60 Kg/m^3. The wide range of variations in water productivity reflects the large variation in rice yield as well as water demand and supply caused by differences in agro-climatic conditions, agronomic and water management practices under which rice and wheat crops are grown in these countries.

The comparison of results obtained from sample fields with those given in Table 5 indicates that for rice-wheat system of Pakistan's Punjab, the physical water productivity of rice is on lower side compared to that of Philippines and Malaysia whereas wheat showed comparable values. Though the physical water productivity of rice for Pakistan' Punjab is comparatively lower than other countries but its economic productivity per unit of land and water may be higher. This could be attributed to the higher market value of Basmati rice produced in Pakistan's Punjab compared to most of the countries in Asia. Because export value of Pakistan's rice is about 4 $/Kg compared to about 2 $/Kg for rice exported by Malaysia and Philippines for the year 2000 (FAOSTAT, 2003). The analysis depicts that a considerable scope exists for enhancing water productivity of the rice-wheat system of Punjab, Pakistan,

through targeting yield increases and water conservation strategies. This will not only help in securing more food for the growing population at the cost of less water input but also help in improving crop income.

Table 5:
Physical water productivity (Kg/m^3) of rice and wheat in terms of yield per unit of water evapotranspired and gross inflow (adopted from TUONG, 1999)

WP_{Y_ET}	WP_{Y_Ig}	Source of data used in calculating water productivity	Location
Rice			
1.39-1.61	0.29-0.39	Bhuiyan et al., (1995), wet seeded rice	Philippines
1.1		Sandu et al., (1980)	India
0.88-0.95	0.33-0.58	Kitamura (1990), dry season	Malaysia
0.89		Mishra et al., (1990)	India
0.4-0.5		Khepar et al., (1997)	India
	0.2-0.4	Bouman and Tuong (2001); 24 data sets	India
		Bouman and Tuong (2001); 16 data sets	
	0.3-1.1		Philippines
Wheat			
1.0-2.0		Turner (1997)	Australia
1.0-1.5	1.0-1.6	Deju and Lu Jingwen (1993), winter wheat	China
		Sharma et al. (1990)	
0.65	0.8	Pinter et al. (1990)	India
0.87	0.79		

3.3 Temporal trends in water productivity

The temporal variations in water productivity for same locations were worth noting as many factors were not changed for sample fields during the study period. Soils, access to groundwater, socio-economic conditions and other physical settings were almost similar over time. The tillage pattern, weedicides/pesticides use, crop duration and seed rate, were not significantly different over time for both the rice and wheat crops. Temporal variation in crop yields and gross inflow for sample fields is presented in Figure 4. The total water input remained higher during second year for both rice and wheat crops. However, most of the sample fields showed higher yield for rice in second year, while no significant variations were observed for wheat.

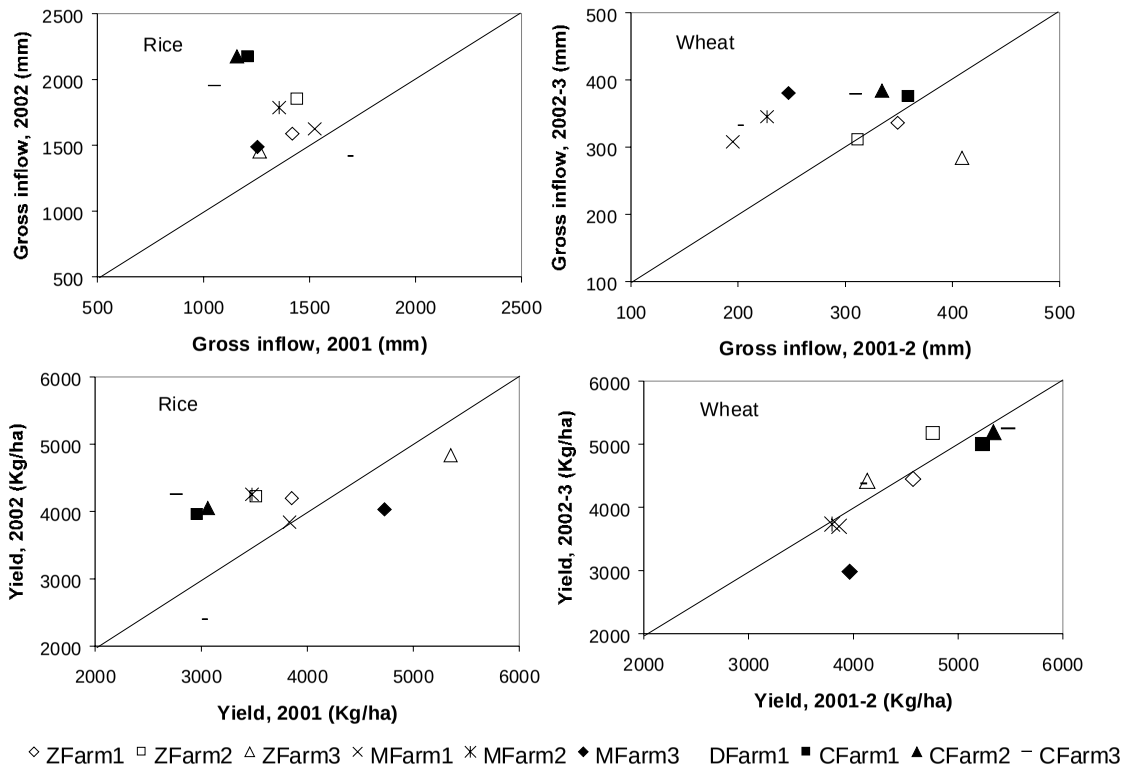

Figure 4:
Temporal variation in water input and yield for rice and wheat, during cropping years 2001-2 and 2002-3, in rice-wheat zone of Punjab, Pakistan

For rice, both physical and economic water productivity were on the lower side during second year despite of yield gains over time (Figure 5a & b). For 7 out of 10 fields, the gross value of production and gross margins per unit of land were higher. However, water productivity estimated in terms of gross value of production and gross margins per unit of water indicated opposite trends as compared with that of land productivity, as evident from Figure 5 a & b, showing that most fields have lower economic returns to water during the second season. The main reason is that farmers tend to sustain or increase their land productivity by additional water. Focusing on change in water productivity, the temporal reduction in water productivity of rice indicated that yield gains were outweighed by higher water inputs. For wheat, despite minimal seasonal variation in land productivity, majority of the sample fields showed lower physical water productivity as shown by Figure 5a. However, economic water productivity (WP_{GVP_Ig} and WP_{GM_Ig}) was on both higher and lower sides (Figure 5a & b). The causal factor for such variation was the amount and timing of rainfall. Fields where rainfall occurs before irrigation, farmers saved one or two irrigation(s), which resulted in higher economic return to water. Also, rainfalls just after irrigation caused yield losses in the poorly drained fields. From a rice-wheat system perspective, the overall economic water productivity declined in the second cropping year (Figure 5 b). This decrease was mainly influenced by the lower water productivity of rice.

The average WP_{Y_Ig} of rice was 16 % lower during 2002 (0.23 Kg/m^3) as compared to 2001 (0.28 Kg/m^3). The productivity of irrigation water was even lower than that of gross inflow, indicating a decline of 30 % as the average value was 0.25 Kg/m^3 for 2002 as compared to 0.36 Kg/m^3 during 2001. Wheat showed a decrease of 19 % in average WP_{Y_Ig} during 2002-3 (1.30 Kg/m^3) when compared with that of 2001-2 (1.60 Kg/m^3). However, for wheat, water productivity per unit of irrigation was 54 percent higher during *rabi* 2002-3 (2.80 Kg/m^3) as compared to that of *rabi* 2001-2 (1.82 Kg/m^3), which was mainly attributed to higher share of rainfall in total water input. The analysis revealed that rainfall variability emerged as the main factor inducing the changes in water productivity over time. The *kharif* 2002 received about 60 % less rainfall as compared to *kharif* 2001 (Table 2). But the *rabi* 2002-3 received about five times more rainfall when compared to *rabi* 2001-2. This forced farmers to imply more irrigation to rice and the average amount of irrigation water increased to 1640 mm during *kharif* 2002 as compared to 1051 mm for *kharif* 2001. Farmers responded with lower irrigations to wheat as they received more water from rainfall during *rabi* 2002-3, though the total water input was higher in the second wheat season. This was the main reason of considerably increased irrigation water productivity of wheat during *rabi* 2002-3 despite of decrease in water productivity per unit of gross inflow.

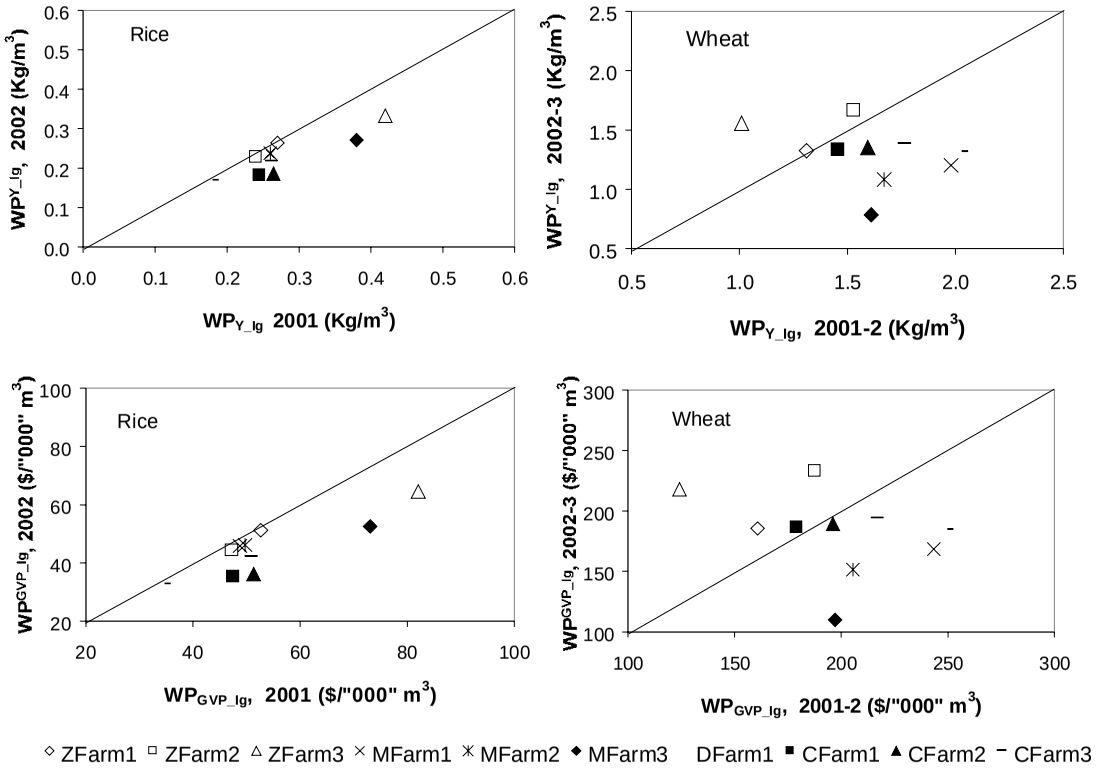

Figure 5a:
Temporal variation in physical and economic water productivity for rice and wheat, during cropping years 2001-2 and 2002-3, in rice-wheat zone of Punjab, Pakistan

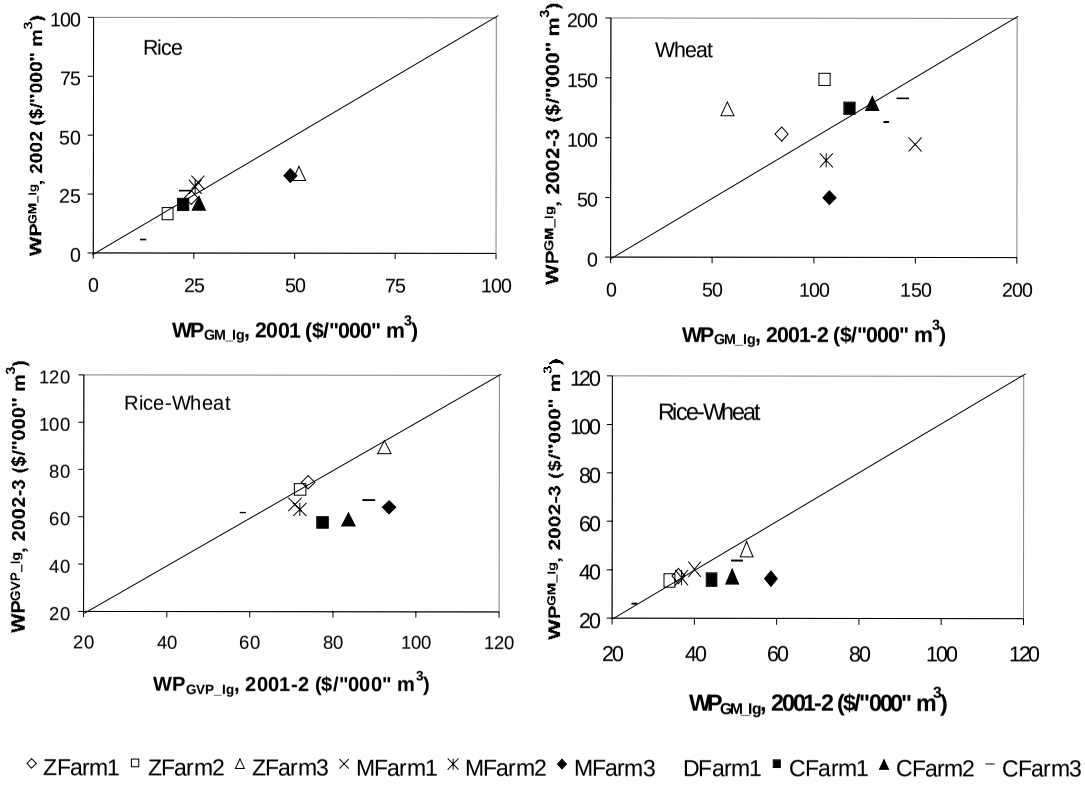

Figure 5b:
Temporal variation in economic water productivity for rice, wheat and rice-wheat rotation, during cropping years 2001-2 and 2002-3, in rice-wheat zone of Punjab, Pakistan

The analyses indicate that for the places where rainfall contributes a more significant proportion of net crop transpiration and is variable over space and time, the concept of marginal productivity should be used. In marginal productivity, we consider the incremental benefit of applying water by irrigation or other means, over and above the benefits we obtain from using available rainfall and soil moisture. The value of considering marginal productivity lies in how water available is best allocated over space, as well as time. A distributed analysis of marginal productivity will show where the best potential lies for reallocation, providing it is physically, politically and administratively possible to manage such reallocations. It will show how average productivity and total production can be increased.

4. Conclusions

In Punjab rice-wheat system water diversions to rice are considerably higher than wheat. However the water actually consumed as transpiration by rice is almost similar to wheat. Consequently, the water productivity of rice is lower than wheat when measured in terms of total water input, irrigation inflow and evapotranspiration. However, the water productivity of rice when measured in terms of actual transpiration is comparable to wheat indicating more economic returns per unit of water actually consumed by the crop. The large amount of water applied to rice is most often recycled and used within the river basin. Therefore, at field scale rice is water inefficient crop but at basin scale it may not be true as water percolated from rice fields is often reused via groundwater abstraction. This indicates that the scale considerations are very important in evaluating the water productivity of various crops.

The water productivity showed considerable variability both in space and time. The main factors influencing spatial inequalities in rice-wheat zone of Pakistan's Punjab were: soils; access to irrigation water, groundwater quality, and agronomic practices. Climatic variability, mainly the timing and amount of rainfall, was found to be the major factor causing temporal changes in water productivity. The overall water productivity in terms of gross inflow for rice, wheat and rice-wheat rotation showed a decline during the cropping year 2002-3 as compared to 2001-2. Neither lower rainfall during *kharif* 2002, nor more rainfall during *rabi* 2002-3 could work effectively in improving the water productivity. Since farmers pumped groundwater excessively to meet water shortages during *kharif* 2002 and could not make optimal use of water, which reduced water productivity and gross margins per unit of water. During the *rabi* 2002-3 the water productivity per unit of gross inflow was lower than that of *rabi* 2002-2, but irrigation water productivity was high. However, this higher irrigation water productivity could not be generalized as more crop per drop because total water input remained higher and no significant gains in yield were observed. Therefore, it is concluded that to sustain or enhance water productivity over time,

more careful response is need to manage the uncontrollable factors such as climatic variability along with the improvements in controllable factors like agronomic and water management practices.

The study also indicates that water productivity analysis should be done through a combined set of water balance and water productivity indicators. Restricting analysis to one or two indicators may not provide the real picture of the water availability, the farmers' way of using it, distribution to various agro-hydrological processes and benefits. This would greatly help water users, water managers and policy makers in the management of available resources in a way that will enhance the productivity of land and water resources.

Acknowledgement

The data used for this study was collected from the research work conducted at Soil Salinity Research Institute (SSRI), Pindi Bhattian and at the farmers' fields. The authors wish to thank SSRI and farmers (Syed Ijlal Haider Zaidi, Sardar Zahoor Ahmed Dogar and Malik Sajad Solomon) for the cooperation. Specially, we acknowledge the Rice-Wheat Consortium (RWC) of Indo-Gangetic Plain for initiating this applied and collaborative research at farmers' fields. Thanks go to Asian Development Bank (ADB) and International Water Management Institute (IWMI) for funding.

more careful response is need to manage the uncontrollable factors such as climatic variability along with the improvements in controllable factors like agronomic and water management practices.

The study also indicates that water productivity analysis should be done through a combined set of water balance and water productivity indicators. Restricting analysis to one or two indicators may not provide the real picture of the water availability, the farmers' way of using it, distribution to various agro-hydrological processes and benefits. This would greatly help water users, water managers and policy makers in the management of available resources in a way that will enhance the productivity of land and water resources.

References

Ahmad, M.D., 2002: Estimation of net groundwater use in irrigated river basins using geo-information techniques: A case study in Rechna Doab, Pakistan. - Ph.D. Thesis, Wageningen University, the Netherlands. 143pp.

Ahmad, M. D., Bastiaanssen, W. G. M. and R. A. Feddes, 2002: Sustainable use of groundwater for irrigation: A numerical analysis of sub-soil water fluxes. - Irrigation and Drainage 51(3): 227-241.

Allen, R. G., Pereira L. S., Raes D. and M. Smith, 1998: Guidelines for computing crop water requirements. - FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization of the United Nations.

Aslam, M., Qureshi, A., S. and V. M. Hornikova, 2002: Water saving strategies for irrigated rice.- Pakistan Council of Research in Water Resources. - Journal of Drainage and Water Management, Vol. 6, January-June 2002, No. 1.

Bastiaanssen, W. G. M., Ahmad, M. D. and Z. Tahir, 2003: Upscaling water productivity in irrigated agriculture using remote-sensing and GIS technologies. - In Kijne, J. W., Barker, R. and D. Molden (Eds.), 2003: Water productivity in agriculture: Limits and opportunities for improvement.- CABI, Wallingford, UK, pp. 289-300.

Bhuiyan, S. I., Sattar, M. A. and M. A. K. Khan, 1995: Improving water use efficiency in rice irrigation through wet seeding. - Irrigation Science 16(1): 1-8.

Bouman, B. A. M. and T. P. Tuong, 2001: Field water management to save water and increase its productivity in irrigated rice. - *Agricultural Water Management*. 49(1), 11-30.

Cassman, K. G. and P. L. Pingali, 1995: Extrapolating trends from long-term experiments to farmers' fields: the case of irrigated rice systems in Asia.- In: Barnett, V.; Payne, R. and Steiner, R. (Eds.), 1995: *Agricultural sustainability economic, environmental, and statistical terms.*- John Wiley and Sons Ltd., London.

Deju, Z. and Lu Jingwen, 1993: The water use efficiency of winter wheat and maize on a salt affected soil in the Huang Huavi river plain of China. - *Agricultural Water Management* 23:67-82.

FAO (Food and Agricultural Organization), 2003: FAOSTAT statistical database. http://apps.fao.org/page/collections?subset=agriculture .

Guerra, L. C., Bhuiyan S. I., Tuong T. P. and R. Barker, 1998: Producing more rice with less water from irrigated systems. - SWIM Paper 5. International Water Management Institute (IWMI), Colombo, Sri Lanka,.

Jalota, S. K. and V. K. Arora, 2002: Model-based assessment of water balance components under different cropping systems in north-west India. - Agricultural Water Management 57: 75-871.

Khepar, S., D., Sondi, S. K., Kumar, S. and K. Singh, 1997: Modeling 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.

Kitamura, Y, 1990: Management of an irrigation system for double cropping culture in the tropical monsoon area.- Technical Bulletin 27, Tropical Agriculture Research Centre, Ministry of Agriculture, Forestry and Fisheries, Tsubkuba, Ibaraki, Japan.

Mishra, H., S.; Rathore, T., R. and R. C. Pant, 1990: Root growth, water potential, and yield of irrigated rice. - Irrigation Science 17: 69-75.

Molden, D. and R. Sakthivadivel, 1999: Water accounting to assess use and productivity of water. - Water Resources Development 15: 55-71.

Molden, D, 1997: Accounting for water use and productivity. - SWIM paper 1. International Water Management Institute (IWMI), Colombo, Sri Lanka,.

PARC, 1982: Consumptive use of water for crops in Pakistan. **-** Pakistan Agricultural Research Council, Final Technical Report: Pk-ARS-69/FG Pa 251, Islamabad, Pakistan: 193 pp.

Pingali, P. L. and M. Shah, 1999: Rice-wheat cropping systems in the Indo-Gangetic plains: Policy redirections for sustainable resource use. - In: Pingali, P.L., (Ed.), 1999:Sustaining rice-wheat production systems: socio-economic and policy issues.- Rice-Wheat Consortium Paper Series 5. Rice-Wheat Consortium for the Indo Gangetic Plains, New Delhi, India.

Pinter, P. J., Zipoli, G., Reginato, R., J., Jackson, R. D., Idso, S. B. and J. P. Hohman, 1990: Canopy temperature as an indicator of differential water use and yield performance among wheat cultivars. - Agricultural Water Management. 18: 35-48.

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

Seckler, D., 1996: New era of water resources management: From dry to wet water savings. Research Report 1. International Water Management Institute, Colombo, Sri Lanak.

Sharma, D., K., Kumar, A. and K. N. Singh, 1990: Effect of irrigation scheduling on growth and evapotranspiration of wheat in sodic soils. - Agricultural Water Management 18: 267-276.

Tabbal D. F., Bouman B. A. M., Bhuiyan S. I., Sibayan E. B. and M. A. Sattar, 2002: On-farm strategies for reducing water input in the irrigated rice; case studies in the Philippines. - Agricultural Water Management 56: 93-112.

Timsina J. and D. J. Connor, 2001: Productivity and management of rice-wheat systems: issues and challenges. - Field Crops Research 69: 93-132.

Tuong, T. P., 1999: Productive water use in rice production: Opportunities and limitations. - Journal of Crop Production 2 (2): 241-264

Turner, N. C., 1997: Further progress in crop water relations. - Advanced Agronomy 58:293-238.

Van Dam, J. C., Hygen, J., Wesseling, J. G., Feddes, R., A., Kabat, P., van Walsum, P. E. V., Groenendijk, P. and C. A. van Diepen, 1997: Simulation of water flow, solute transport and plant growth in the Soil-Water-Atmosphere-Plant environment theory of SWAP version 2.0. - Report 71., Department of Water Resources, Wageningen Agricultural University, Technical Doc. 45 DLO Winand Staring Centre, Wageningen Agricultural University, The Netherlands.

van der Hoek, W., Sakthivadivel, R., Renshaw, M., Silver, J. B., Birley, M. H. and F. Konradsen, 2001: Alternate wet/dry irrigation in rice cultivation: A practical way to save water and control malaria and Japanese encephalitis? - Research Report 47. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Addresses of the Authors:

Mobin-ud-Din Ahmad and Hugh Turral
International Water Management Institute (IWMI), Global Research Division,
P. O. Box. 2075, Colombo, Sri Lanka.
Email: a.mobin@cgiar.org (Mobin-ud-Din Ahmad) and h.turral@cgiar.org (Hugh Turral)

Iyas Masih
International Water Management Institute (IWMI), Regional office for Pakistan,
12 km Multan Road, Chowk Thokar Niaz Baig, Lahore, Pakistan.
Email: i.masih@cgiar.org