Scale Effects on Water Use Efficiency and Productivity: A Case Study from UPRIIS, Philippines

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EXTENDED ABSTRACT

Increasing water productivity of irrigated rice remains the most promising challenge to tackle the increasing water scarcity problems. The aim of this study is, therefore, to measure scale effects on water productivity through water accounting coupled with remote sensing and geographic information system (GIS) in rice-based irrigation system of District I of the Upper Pampanga River Integrated Irrigation System (UPRIIS), Philippines. The water accounting is applied at five different spatial scales to study water savings and impacts on different scales. The spatial scale ranges from a micro scale at the size of farmers field (area of 1 ha), to sub-irrigation canal scale (10,000 ha) and a system scale (area of 18,000 ha) covering the entire District I area. Daily measurements of all surface water inflows and outflows, rainfall, evapotranspiration, and amounts of water internally reused through check dams and shallow pumping are summed into seasonal totals, from November 19, 2000 to May 18, 2001 for five spatial scale units ranging from 1 to 18,000 ha. Water accounting technique is applied to measure performance indicators of the water productivity at each spatial scale.

Results from a field scale show that water productivity per unit of delivered water is higher than all spatial scales due to best management practices and high input of fertilizers (180 kg/ha). The process fraction of gross inflow is very high which shows that farmers put lot of efforts to make full use of irrigation water and rainfall. These observations at field scales indicate that farmers are very effective in capturing and utilizing all water input. However, the amount of net surface water input (rainfall plus irrigation) per unit area decreases and the process fraction, depleted fraction, water productivity, and amount of water reuse increases with increasing spatial scale. In total, 57% of all available surface water is reused by check dams and 17% by pumping. The process fraction of all surface water input (irrigation and rainfall) is very high (0.71) at the field scale and it is relatively low (0.15) at TRIS-L scale but gradually increases with spatial scale up to 0.22 for all scale units combined. The major reason of improving water productivity is due to large volume of re-used water (30 % of water lost through ET_a of rice) from 15 small check dams, hundreds of small farm ponds and 1451 pumps installed in District I. Water productivity with respect to ET of rice varies between 1.75 and 0.8 kg grain m^{-3} water at field and District scale). The only option to increase WP_{ET} at large spatial scales is again crop protection measures such as pest and disease control and reduced post-harvest losses. The overall water productivity with respect to available water ($WP_{available}$) is 0.45 kg grain m^{-3} water, which compares well with the average of 0.4 kg grain m^{-3} water for rice at the field level. At the field scale, the $WP_{available}$ is 1.25 kg grain m^{-3} water, suggesting that there is considerable scope for improvement in the study area.

The results show that water re-use plays a dominant role in the growth of a rice crop during the dry season. The finding shows that scale effects are important for understanding, planning for water saving and for planning appropriate measures to increase water productivity. The results clearly indicate that the quantification of volumes of water re-use is crucial for understanding and finding real water saving possibilities at the irrigation system level. These findings would lead to an improvement in the water use efficiency and water productivity of irrigated rice systems.

1. INTRODUCTION

The food security of Asia depends largely on the irrigated rice production system, which is a major user of fresh water. Some 75% of the world's annual rice production is harvested from 79 million ha of irrigated lowland rice, mainly in Asia, where it accounts for 40-46% of the net irrigated area of all crops (Dawe, 2005). Because of its large area, and because rice receives relatively much water, Bouman et al. (2006) estimated that 34-43% of the world's irrigation water is used to irrigate rice. In Asia, rice water use figure varies from 30-35% for South Asia to 64-83% for Southeast Asia (Dawe, 2005). However, water resources are getting increasingly scarce and rice is a main target for water-saving initiatives (Rijsberman, 2006).

Total seasonal water input to rice fields (rainfall plus irrigation) is up to 2-3 times more than for other cereals (Tuong et al., 2005). It varies from as little as 400 mm in heavy clay soils with shallow groundwater tables to more than 2,000 mm in coarse-textured soils with deep groundwater tables (Bouman and Tuong, 2001). Around 1,300-1,500 mm is a typical value for irrigated rice in Asia. Because of these large water inputs, the water productivity of rice with respect to water inputs is quite low: the average reported value for rice at the field level of 0.4 kg grain m^{-3} water is about two times smaller than that of wheat (Tuong et al., 2005). The large water inputs are mostly caused by surface drainage and seepage and percolation flows from the continuously ponded fields into the groundwater, creeks, and drains. Seepage and percolation flows account for about 25-50% of all water inputs in heavy soils with shallow (20-50 cm depth) groundwater tables to 50-85% in coarse-textured soils with groundwater tables of 1.5 m depth or more (Choudhury et al., 2007). Therefore, most water-saving technologies developed at the field level aim to reduce seepage and percolation flows (Tuong et al., 2005). However, though these flows are losses at the field level, they can be captured and reused downstream and do not necessarily lead to true water depletion at the irrigation system level. This water can be reused by blocking creeks and diverting the water into new irrigation canals, by direct pumping from creeks and drains, or by pumping from (shallow) groundwater. In this way, one farmer's water loss may be another farmer's water gain (Seckler, 1996). In view of this possibility, water use efficiency at the system level is deemed higher than at the individual field level. Therefore, it has been argued that the efficiency of water use and the water productivity of rice may increase with increasing spatial scale and may be much higher at the irrigation system level than at the individual field level (Tuong et al., 2005).

To test this hypothesis, water flows within an irrigation system would need to be tracked at different spatial scales. Also, the water flows would need to be separated into reusable flows and real depletion flows (such as evapotranspiration), and amounts of water reuse would need to be estimated. Loeve et al. (2004) carried out the first study to measure water flows at "micro" and "meso" scales in the 467,000-ha Zanghue Irrigation System (ZIS), in Hubei Province, China, in which 27% of the area was cropped with lowland rice. The micro scales consisted of small sets of farmers' fields that were together less than 1 ha, and the meso scales were areas within the irrigation system of 287 and 606 ha. Water inflows were also available for main canal command areas of 28,000-196,000 ha and for the whole irrigation system. Water productivity decreased from micro to meso scale, but increased from meso scale to canal command area and to the whole irrigation system. The case study, however, involved mainly upland crops such as wheat, cotton and sugar cane. The number of scale levels at which detailed flow measurements were made, however, was not large enough to make solid conclusions on the relationship between scale and water productivity and other water use parameters for irrigated rice system. Secondly, most of the previous studies have mainly focused on measuring the water productivity of either a farm or irrigation system for irrigated rice. Such types of analysis do not provide true information about the water productivity links across scales which could be helpful to measure real water savings.

Therefore, a comprehensive study needs to be done to fully understand water use and productivity at different spatial scale levels in rice-irrigated system. This paper presents results for a study on water use in a rice-based surface irrigation system in the Philippines from farmer's field to irrigation system level. Using the water accounting principles of Molden (1997), water productivity and various water use indicators are calculated for five different spatial scale levels.

This study focuses on irrigated rice systems in the Philippines, where irrigated rice accounts for 61% of the 3.4 million ha of rice production area. The objective of the paper is to quantify the current water use, and productivity at five (5) different spatial scales (varying from 1 ha to 20,000 ha) in District I of Upper Pampanga River Integrated Irrigation System (UPRIIS), Philippines through water accounting method. The ultimate aim is to test the hypothesis that the efficiency of water use and water productivity of rice increases with increasing spatial scale because of the reuse of seepage, percolation, and drainage water. This analysis would help to determine current levels of efficiency and to develop strategies to improve water productivity.

2. DESCRIPTION OF STUDY AREA

The study area is District I of the 102,000-ha Upper Pampanga River Integrated Irrigation System (UPRIIS) in Central Luzon, Philippines (Figure 1). UPRIIS is owned and operated by the National Irrigation Administration (NIA) of the Philippines with the main purpose of providing irrigation water to rice fields. District I has a total area of 28,205 ha, including rice fields (dominant land use), upland crops, vegetables, roads, settlements, and water bodies. The district is bounded by the Talavera River to the east and the Ilog Baliwag River to the west, and consists of an upper part, called the Talavera River Irrigation System-Lower (TRISL), and a lower part, called the Santo Domingo Area (SDA). Water is supplied by Diversion Canal No. 1, which gets its water from the Pantabangan reservoir, and the TRIS main canal, which gets its water from the Talavera River through a run-off-the-river diversion dam. The major direction of water flow is from northeast to southwest, though locally, water flows in various directions according to topography. The TRIS main canal first supplies water to an irrigation system north of, and contiguous to, District I, called TRIS-Upper. In TRIS-L, the De Babuyan check dam raises the water level in the Sapang Kawayan creek and the water is diverted into the Santo Domingo Main Canal that irrigates the SDA. The area is quite flat, with elevations of around 20 m above sea level. The climate is characterized by two pronounced seasons, dry from November to April and wet for the rest of the

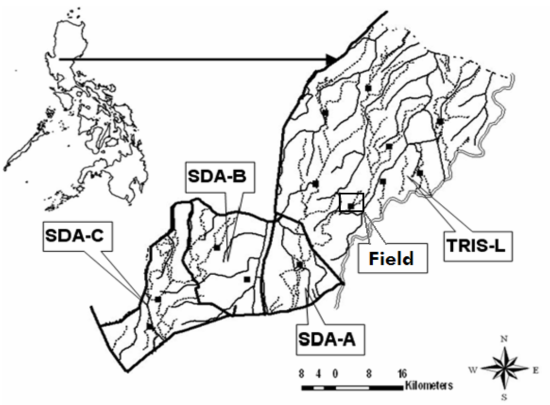

Figure 1: Different spatial scales in District I where check dams (▪), unit boundaries (▬▬), canals (——), creeks (⋯⋯) and rivers (══)

year. The average annual rainfall is about 1900 mm, of which 90% falls in the wet season (Tabbal et al., 2002).

The study was conducted in the 2000-2001 dry season. It started with the first release of water in the main canals on November 19, 2000, and ended with the harvest of the last rice crops on May 18, 2001. Water is scarce, upland crops such as onion, tomato, watermelon and maize are grown in the dry season. Use of small pumps is common among the upper and lower reaches of the lateral canals in District I.

Five rice fields were selected in TRIS-L scale to capture the differences between on-farm irrigation water use of fields. District I was subdivided into five spatial scales (Figure 1): Field (1 ha), TRIS-L (11239 ha), TRIS-L + SDA-A (12752 ha), TRIS-L + SDA-AB (14992 ha), and TRIS-L + SDA-ABC (18003 ha). All boundaries consist of roads, which were selected that all surface water flowing in and out of the areas could be measured.

3. METHODOLOGY

3.1 Water Accounting

The water accounting framework is basically an analysis of the water balance, in which the outflows are classified according to their use, or potential use, within or outside that area (Table 1). The 3-dimensional boundaries of the study area were the horizontal outer boundaries of the five spatial scales, the top of the surface/vegetation, and the bottom of the rootzone. The water accounting was focused on surface water, and the net flow of water across the lower boundary (rootzone) was separately analyzed as the closing term of the water balance. All water flows were computed as seasonal totals, from November 19, 2000, till May 18, 2001. The gross inflow was rainfall plus all surface irrigation water. The net inflow was the gross inflow minus the change in water stored at the surface (mainly in the canals) and in water stored in the rootzone of the crops from the beginning to the end of the cropping season. Since the canals were dry before the start of the season and after harvest of the last crops, the change in surface water storage was zero. The change in stored soil water in the rootzone was neglected since the dry season crop followed straight after a wet season crop and assumption was made that the amount of soil water was the same after a harvested wet–season crop and after a harvested dry–season crop. Therefore, the net inflow was the same as the gross inflow. All surface outflows were considered “committed” when they flowed into downstream in the irrigated area of District I. All water flowing out of District

I was considered "uncommitted" since there was no immediate major water user downstream of District I. The only outflow considered "depletion" was evapotranspiration (ET) since no water percolated to irretrievably deep or saline groundwater. Since the purpose of UPRIIS is to irrigate rice, only rice ET was considered as "process depletion," and all nonrice ET as nonprocess depletion.

Water balance

The water balance of each spatial unit was calculated as

$$\delta W = I - O - ET \quad \text{(mm)} \qquad (1)$$

where I = net surface inflow by irrigation and rainfall, O = surface outflows, and ET = evapotranspiration of all rice and nonrice surfaces. The term δW should be interpreted as the net result of water percolating downward, capillary rise, and groundwater pumping across the lower boundary (bottom of the rootzone) of the study area. These components could not be as accurately assessed as the surface water flows, and, in the case of percolation, could not be readily classified as "committed" or "uncommitted." Moreover, part (if not all) of the water pumped from the groundwater is in fact reuse of percolation water and is analyzed separately as internal water reuse. When δW is positive, it means that water is added to the groundwater or to the soil layers below the rootzone; when it is negative, it means that water is extracted from the groundwater or from the soil layers below the rootzone (Bouman et al., 2007). It should be noted, however, that since δW is calculated as the closing term of the water balance, it also includes all errors in the measurement of the individual water balance components.

Internal water reuse

UPRIIS was designed to reuse surface water through check dams in creeks and drainage ways. Farmers added to this water reuse by constructing their own dams that have subsequently been formalized by the irrigation system management. There are now a total of 15 check dams in District I, which are operated and maintained by either NIA or by groups of farmers. Water flows in inlets were estimated at nine of the 15 check dams (see below). Farmers also informally reuse water by pumping from shallow groundwater, creeks, and drains. All farmers were surveyed in the area on pump ownership and pump use, and counted the number of pumps in each of the spatial units. 50 farmer representatives were selected for the different types of pumps and pump use, and monitored their pump operations during the growing season. Each pump was calibrated, and pumped water volumes from surface water and groundwater were obtained by multiplying calibrated flow rates by recorded durations of pumping. The pumped water volumes were extrapolated to the spatial scales using the total number of pumps in each unit. More details can be found at Hafeez et al., 2007.

Groundwater pumping can mean the reuse of water percolated down from rice fields and/or the use of groundwater that originated from outside the area. The total volume of water percolating down from rice fields was estimated by multiplying the rice area by a mean percolation rate of 2 mm d^{-1} as reported for the TRIS and SDA areas by Lucero (1984). This calculation is a conservative estimate of total percolation flows through the lower boundaries since it does not include water percolating from waterways and nonrice fields.

The change in groundwater storage from the start to the end of the growing season was also estimated by measuring groundwater depths in 50 observation wells in District I. The differences in depth were multiplied by a soil-type specific storage coefficient that was estimated as the difference in water content between saturation and field capacity derived from data reported by Ramos (1986). Changes in groundwater storage were obtained by overlaying the spatial units with the soil map and with Thiessen polygons around the observation wells. The calculated change in groundwater storage indicates whether net groundwater recharge or depletion takes place.

Water flow measurements at Field level

At three field sites, the amounts of irrigation, drainage, and rainfall were measured throughout the growing season. The discharge Q [m^3 s^{-1}] was measured using V-notch weirs and cut throat flumes. Amount of irrigation was calculated by integrating the discharge over each time-step between two readings of the water height in the weir and the flume. Groundwater level was monitored with PVC pipes perforated 50 cm below field level. The surface water level was determined daily at both sites. Percolation rate at the sites was measured inside covered metal cylinders. Daily rainfall was taken from the meteostation at the sites. Yield was measured from at the harvest time. More detail is given in (Belder et al., 2004).

Water flow measurements at system level

Surface in- and outflows were measured twice a day by tracking all flows through drains, creeks, channels, or culverts (a total of 158 points) underneath the roads that formed the boundaries of the spatial scales. For most open waterways, water depth with installed staff gauges was measured and obtained flow volumes from rating curves established (R^2 of 0.95) using current meters and measured cross sections. Water flows were estimated in inlets at 9 of the 15 check dams by installing staff gauges and obtaining flow volumes from rating curves established (R^2 of 0.95) using current meters. Rainfall was measured from eight rain gauges installed throughout District I, and total volume of rainfall for each spatial unit was estimated by spatial extrapolation using Thiessen polygons. Seasonal actual evapotranspiration (ET_a) was estimated through the Surface Energy Balance Algorithm for Land (SEBAL; Bastiaanssen, 1995) approach using six TERRA/MODIS and three Landsat 7 ETM+ optical satellite images over the irrigation season. All meteorological data for calibration of SEBAL, such as air temperature, skin water temperature, soil temperature, air humidity, wind speed, and solar radiation, were collected hourly on the day of satellite overpass from two weather stations in District I. ET_a was divided over rice (process outflow) and other land covers (non-process outflow) based on a supervised land use classification using a Landsat image from March 31 for all the spatial units. Further details on the measurements are given by Hafeez (2003).

Water performance indicators

For each spatial unit, a number of water accounting indicators and water productivity (WP) were calculated following the procedures presented by Molden (1997). Rice yield to calculate WP was obtained from the NIA (Hafeez, 2003), which kept track of the yield of each farmer in the area. For each spatial scale, total rice production was obtained by summing yields of individual farmers.

4. RESULTS AND DISCUSSION

General characteristics and results of the water balancing and water accounting are given for each spatial unit in Table 1. The sizes of the spatial scale varied from farmer's fields (1 ha) to about 18,000 ha. Rice covered about 75% of the surface area in most of the spatial scales excluding field scale where rice covered area was 98%. In TRIS-L + SDA-ABC scale, the rice area covered only 65% of the total area, probably because less water was available here, which prompted farmers to grow less water-demanding crops. Rice yields were highest at the field scale, followed in the upstream area TRIS-L and lowest in TRIS-L+SDA-ABC, with an absolute difference of 2.29 t ha^{-1}.

4.1 Water Accounting and balance

Results of the water balancing and water accounting are given for each spatial scale in Table 1. At the field scale, average daily crop potential evapotranspiration (ET_c) was 4.6 mm d^{-1} for Philippines Rice Research Institute (PhilRice). Total ET_c was 435 mm from crop establishment to harvesting. Rainfall was 91 mm during the 2001 dry season at PhilRice. The dry season was relatively wet, because average rainfall at PhilRice in the same period of the year from 1990-2000 was 48 mm. The maximum diurnal precipitation was 22 mm at PhilRice on March 30 2001. Average irrigation water use was 518 mm for the season at PhilRice. Bouman (2001) reported typical values of 1,500-2,000 mm for lowland areas (including water used for land preparation).

Table 1: Main characteristics and water accounting components for 5 spatial scales in District I

Descriptor	Field[1]	TRISL	TRISL + SDA-A	TRISL + SDA-AB	TRISL + SDA-ABC
Total area (ha)	1.08	11,239	12,752	14,992	18,003
Rice area (ha)	1.00	8,713	9,890	11,599	13,571
Upland crop (ha)	0.00	886	972	1,214	1,629
Rest (ha)	0.08	1,640	1,890	2,179	2,803
Rice yield (t ha^{-1})	7.6	6.09	5.41	5.47	5.31
Farmers (number)	3	7,207	7,958	8,859	9,910
Pumps (number)	0	519	628	735	1154
Water flows	(m^3)		(10^6 m^3)		
Irrigation inflow	5180	355	355	358	358
Rain inflow	910	33	37	41	50
Committed outflow	0	231	245	239	250
Uncommitted outflow	0	49	49	49	49
Available water	6090	157	147	160	159
Rice ET depletion	4350	57	65	77	90
Other ET depletion	100	11	13	16	22
Balance	1640	40	20	18	-3
Internal water flows	(m^3)		(10^6 m^3)		
Rice field percolation	1450	32	36	42	49
Reuse by check dams	0	54	54	61	90
Pumping surface water	0	1	1	1	1
Pumping groundwater	0	14	16	17	26
Groundwater change	0	-3	-3	-5	-7

At larger spatial scales, irrigation comprised 88-97% of all surface water inflows due to limited rainfall during the season. Irrigation water inflow and total water outflows generally increased with increasing spatial scale, indicating that large amounts of surface water flowed overland through the system without being depleted. Out of all surface water outflows, only 49 x 10^6 m^3 was uncommitted as it flowed directly into the Talavera River from TRIS-L. All other outflows were committed and flowed either into another spatial scales or into the downstream irrigated area of District I. Scales that had a relatively large irrigation water inflow also had a relatively large surface water outflow. Hafeez et al. (2007) reported that per unit rice area, total net applied surface water (all surface inflows minus surface outflows) decreased linearly with increasing scale from 1,200 mm at 11,000 ha to 800 mm at 18,000 ha. The volume of rice and nonrice ET increased linearly with spatial scale, indicating uniform evaporation conditions within District I. Per unit area, the average rice ET was 665 mm for the whole season and 3.7 mm d^{-1}. The nonrice ET was 503 mm for the whole season and 2.8 mm d^{-1}.

The water balance term (net surface inflows minus surface outflows and all ET) was relatively small, being 1-10% of total surface inflows at different scales. The term was positive for all spatial units except for the combination of all units, for which it was close to 0. These positive values suggest that water percolated down and recharged groundwater as subsurface water into neighbouring scales.

Water performance indicators

The performance indicators are given in Table 2. PF of all surface water input (irrigation and rainfall) was very high (0.71) at the field scale and it was relatively low (0.15) at TRIS-L scale but gradually increased with spatial scale up to 0.22 for all scale units combined (Figure 2). PF of available water was much higher at field level and then it linearly increased with spatial scale up to 36% at TRISL, partly because of the relatively large uncommitted surface water outflows and it increased to a maximum of 57% at District scale. PF of depleted water was 0.98 at field scale. While PF was 0.8 at District scale, which is not changing much with the scales because the area covered by rice remains similar to 75%. In a comparable-sized area of 28,500 ha in the ZIS in China, the PF of depleted water was 27% for a rice area of 19% (Loeve et al., 2004).

Table 2: PF, DF, and WP for five spatial scales in District I

Descriptor	SDA-ABC	TRISL	TRISL + SDA-A	TRISL + SDA-AB	TRISL + SDA-ABC
PF_{gross}	0.71	0.15	0.17	0.19	0.22
$PF_{available}$	0.71	0.36	0.45	0.48	0.57
$PF_{depleted}$	0.98	0.84	0.84	0.83	0.8
DF_{gross}	0.73	0.18	0.2	0.23	0.28
$DF_{available}$	0.73	0.43	0.53	0.58	0.71
WP (kg grain m^{-3} water)					
WP_{gross}	1.25	0.14	0.14	0.16	0.18
$WP_{available}$	1.25	0.34	0.36	0.4	0.45
WP_{riceET}	1.75	0.92	0.82	0.82	0.8

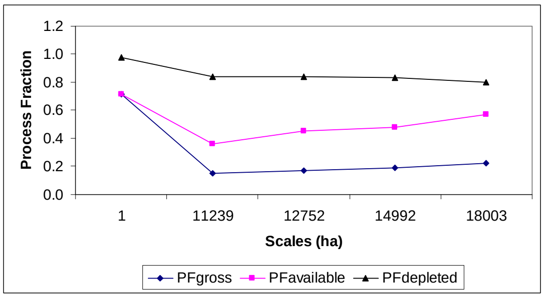

Figure 2: Process fraction trends across scales

DF of all surface water input and of available water was higher at field scale than other four spatial scales and followed the same trends as the PF (Figure 3). Again, with the large uncommitted outflow of water, the DF of available water was lower across all larger spatial scales. The overall DF of available water was 71%, which is similar to the 67% reported for the same scale size in ZIS. Like the PF of depleted water, the fraction of depleted water was quite high and possibilities to increase it seem limited. DF can be increased by reducing the amount of seepage and percolation water and/or increasing the internal reuse of water.

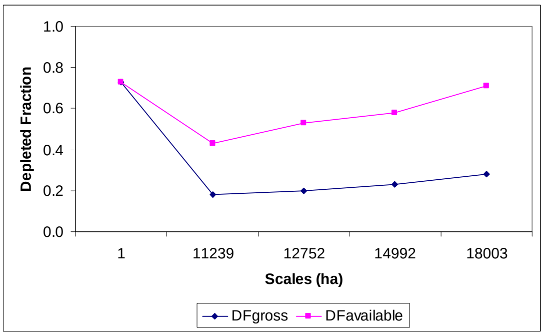

Figure 3: Depleted fraction trends across scales

WP with respect to gross inflow and available water was also higher at field scale and followed the same trend as the process fractions (Figure 4). The overall WP with respect to available water ($WP_{available}$) was 0.45 kg grain m^{-3} water, which compares well with the average of 0.4 kg grain m^{-3} water for rice at the field level (Tuong et al., 2005). At the field scale, the $WP_{available}$ is 1.25 kg grain m^{-3} water, suggesting that there is considerable scope for improvement in the study area. The nitrogen (N) fertilizer application rate in these fields was as high as 180 kg N ha^{-1}, and since average fertilizer N use in Central Luzon where UPRIIS is located is only about 100 kg ha^{-1}, there may be scope to increase yields through increased fertilizer N application. Secondly, the $WP_{available}$ can be increased by reducing the non-beneficial outflows from rice fields. . In study area, there may be great scope to reduce non-beneficial outflows by shortening the total operation time (182 days) of the irrigation system to 120 days (farmer's fields). WP with respect to ET (WP_{ET}) of rice was varying between 1.75 and 0.8 kg grain m^{-3} water at field and District scale). The only option to increase WP_{ET} at large spatial scales is again crop protection measures such as pest and disease control and reduced post-harvest losses.

Water reuse

Data on water reuse are given in Table 1. At the highest aggregation level, the reuse of surface water was 22% of all applied surface water and 57% of all available surface water. A large number of farmers used pumps for complete or supplemental irrigation. On average, 12% of the farmers owned a pump, though more farmers used a pump because of shared use and rental arrangements (Moya et al., 2002). Pumping from surface water was negligible and nearly all water was pumped from the shallow groundwater. Hafeez et al. (2007) estimated that total (re)use of water through pumping increased by 1.3 10^6 m^3 per 1,000 ha. At the highest aggregation level, the water (re)use by pumping was 7% of the applied surface water and 17% of the available water.

Percolation and groundwater recharge

The estimated amount of percolating water from rice fields was about 1-3 times the amount of water pumped from the groundwater across the spatial units (Table 1). Despite this percolation flow, which can be interpreted as recharging the groundwater, groundwater tables in the observation wells decreased from an average depth of 2.3 m at the start to 3.4 m (standard error 0.2 m) at the end of the growing season. Though the estimated changes in stored groundwater were small, the negative values suggest that groundwater leaked out of the irrigated area.

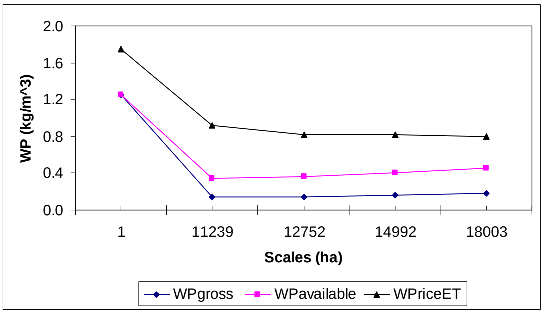

Figure 4: Water productivity trends across scales

5. CONCLUSIONS AND DISCUSSION

Results from a field scale shows that water productivity per unit of delivered water is higher than all spatial scales due to best management practices and high input of fertilizers. The process fraction of gross inflow is very high which shows that farmers put lot of efforts to make full use of irrigation water and rainfall. These observations at field scales indicate that farmers are very effective in capturing and utilizing all water input.

At larger scales, the results support the hypothesis that water use becomes more efficient with increasing scale because of water reuse: the amount of net surface water input decreased and the process fraction, depleted fraction, water productivity, and amount of water reuse increased with increasing spatial scale. The water use calculation shows that 22% of the applied surface water was reused by internal check dams and 7% through pumping from shallow groundwater in the whole of the study area. Most of the water applied to District I is used within the district, and only 49 10^6 m^3 is lost as uncommitted water and could potentially be saved or used for rice production in downstream within the district.

The results of the study are influenced by the sizes and locations of the spatial units which were established based on the existing road network and accessibility. Although the relationships between water accounting and performance indicators with spatial scale will be different with another layout of spatial scales, the trends have found will be the same. A hydrological model study is needed next to quantify the options to improve the efficiency and productivity of water use as discussed above, and to disentangle spatial tradeoffs in water accounting and water performance indicators.

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