ARTICLE

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Issues of scale in water productivity in the Zhanghe irrigation system: implications for irrigation in the basin context

Abstract In the context of increased competition for water, growing more rice with less water will be one of the major challenges of the 21st century. This paper examines water savings and issues of scale in water productivity. The main objective is to understand if and how field-scale interventions scale up to subbasin-scale water savings in the Zhanghe Irrigation District (ZID) in Hubei Province, central China. Our results confirmed that on-farm water-saving practices result in higher water productivity per unit of irrigation water at the field scale due to lower irrigation water input. However, the question is, if these field-scale practices have led to "real" water savings; savings which can be transferred to other agricultural and non-agricultural uses without lowering existing production levels. To investigate this question, we examined water use and productivity at four different scales: field scale, meso scale, main canal command scale, and subbasin scale using the water accounting methodology. The study clearly demonstrates the high dependence on the scale of water use and productivity parameters. Depleted fraction and water productivity per unit of gross inflow and irrigation water varied dramatically across scale. Thus, it is not possible to conclude from field-scale observations that basin level water savings will or will not take place. The major reasons for these scale effects are the lateral flow of water across boundaries, differing land use patterns across scales, and changing water management patterns across scales. In the ZID, going from field and meso scale to even larger scales, water productivity per unit of irrigation increases to even higher levels than at the field scale. Here it becomes clear that the ZID, with its possibilities of reuse of drainage return flows and capturing rainfall and runoff in all the reservoirs within the system, is very effective in capturing and using water productively. Factors that influence water productivity and depleted fraction are on-farm water savings as well as the reuse of drainage water, effective capturing and utilization of rain, and canal water management. The scope for additional real water savings in the Zhanghe Irrigation District is limited. Only 13% of the combined rainfall and Zhanghe reservoir irrigation water releases flow out of the basin. A further reduction in drainage surface outflow from the ZID may have negative downstream effects on other water uses, including environmental uses. The main lessons learned are that (1) employing a combination of factors—on-farm practices, reuse, and canal operations—can be an effective means of conserving water resources within irrigation systems, (2) the scope for savings must be considered by an analysis at larger scales (i.e. irrigation system or basin scale), and may be less than thought because of the interactions of these factors. The results clearly indicate that scale effects are important for understanding and planning for water savings and water productivity.

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Introduction

Growing more rice with less water is one of the major challenges of the 21st century. Rapidly increasing water demands from cities, industries, and environmental uses will put a strain on water resources in many river basins and food security is challenged by an ever increasing food demand from a growing population in the coming decades (Rijsberman and Molden 2001). The per capita freshwater availability in China is among the lowest in Asia (FAO 2003), and is still declining and it is becoming increasingly difficult to develop new freshwater sources. Much of the water needed has to come from water savings; and rice, a water-intensive crop and the most important staple food in Asia (Maclean et al. 2002) and China, is a major target for such savings. In southern China, the major rice growing area, more than 90% of the total irrigation water is allocated to rice production (Mao 1997).

In response to fresh water shortages, China has already developed many practices for farmers to deliver less water to their rice fields and thus offers an ideal opportunity for learning. These methods are collectively known as water-saving irrigation (WSI) practices and many success stories are reported (Wang 1992; Mao 1993; Li and Cui 1996; Peng et al. 1997; Li et al. 1998; Wu 1998; Li 1999; Belder et al. 2004). Li et al. (2003) give an extensive overview of the developments in WSI research in China. One promising practice Intermittent Submerged Irrigation (ISI), which has been adopted in South China (Li et al. 1999) is being implemented on a large scale in the Zhanghe Irrigation District (ZID). Dong et al. (2004 in this volume) describe in detail actual on-farm practice in two study sites in Zhanghe Irrigation System. A question of global interest is whether this water saving practice has led to "real" water savings—i.e. water that can be transferred to other uses without substantial production lost within agriculture.

This study uses the concepts water saving and water productivity instead of the more traditional concept water use efficiency. The fundamental problem with the term water-use efficiency, is that it considers outflow out of the area concerned as a loss (Seckler 1996). This is invalid for the part of the outflow that is reused downstream. Keller and Keller (1995) refer to this efficiency term as "classical efficiency".

Dong et al. (2004) in this journal quantify the water productivity under ISI and non-ISI practices in the Zhanghe Irrigation System (ZIS) at field scale. The objective of this paper is to quantify the water productivity at different scales ranging from the field scale to the subbasin scale to get a better understanding of the "scaling up" of field-level water-saving practices. With this knowledge, important insights into the design and management of irrigation are gained that will lead to transferable water savings.

Methodology

Scales and water saving

As described in Dong et al. (2001), the term "water saving" has different meanings to different people at different scales. Farmers would typically like to make some more money from their resources and, if they have to pay for water, either by paying energy costs or costs of a service provider, they may have sufficient incentive to use less water. In the case of ZIS, as a response to the system delivering less water to agriculture and more to other uses, farmers have to use less water while attempting to get high yields. At the field scale, "water saving" most often refers to a reduction in irrigation water applied to crops (Tuong and Bhuiyan 1999).

In many (water-short) river basins of the world, demand is growing for good-quality water for non-agricultural uses—cities, and industries. In these situations, irrigated rice and environmental uses are considered a relatively low-valued use of water and there is pressure to meet other demands first and then let agriculture and environment have the remaining water. At the basin scale, a common societal interest is reducing the total amount of water depleted by irrigated agriculture while maintaining or increasing the production and transfer of water to other higher-valued uses.

Our objective was to investigate if water saving practices at the field scale led to real water savings at the subbasin scale. To assess the impact of field scale interventions on the subbasin scale, ideally one would like to investigate a situation before the implementation of any water saving practices, i.e. ISI are implemented in an area and a situation after water saving practices are implemented in the entire irrigation system. Additionally measurements would have been taken at different scales to asses the different factors at different scales contributing to the upscaling of water savings. Unfortunately such an area and dataset does not exist. Time series analyses of water productivity in Zhanghe Irrigation District (subbasin scale) were performed (Loeve et al. 2004) and it was concluded that water productivity over time increased dramatically, but can only partly be contributed to the implementation of water saving irrigation practices.

For this paper we examined water use and productivity at four different scales: field scale, meso scale, main canal command scale, and subbasin scale in the rice growing season of 2000.

Subbasin scale: the Zhanghe Irrigation District

The ZID is situated in Hubei Province in central China, north of the Yangtze River. This area is one of the most important bases of commodity grain in Hubei Province. The Zhanghe Irrigation System is one of the typical large-size irrigation systems in China, with a total area of 554,000 ha, of which an area of about 160,000 ha are irrigated.

The Zhanghe Reservoir, built on a tributary of the Yangtze River, supplies most of the irrigation water to the ZIS. The reservoir was designed for multipurpose uses including irrigation, flood control, domestic water supply, industrial use, and hydropower generation. In the ZIS, the canal system includes one general main canal, five main canals, and many branch canals with a total length of more than 7,000 km. Besides these, there are tens of thousands of medium- or small-sized reservoirs, small ponds, and pumping stations in the area partly incorporated into the system but sometimes operating independently. Downstream of the ZID is Chenghu Lake, which captures drainage flows from the ZIS. The main crops are rice, winter wheat, sesame, and soybean, with paddy fields occupying about 80% of the total irrigation area. For this research, the ZID is considered to be the subbasin scale.

Main canal command scale

Although there are five main canals in the ZIS, only four of them are considered in this research, since satellite image data for a part of the Fourth Main Canal command area were not available. The

Table 1 Water-accounting indicators and terminology (Molden 1997)

Indicator	Description
Gross inflow	Total amount of inflow crossing the boundaries of the domain. In this case, irrigation water, rainfall, and drainage water (we assume zero lateral groundwater flow)
Net inflow	Gross inflow less the change in storage over the time period of interest within the domain
Committed water	Part of the outflow that is reserved for other downstream uses such as water rights or environmental uses
Available water	Amount of water available to a service or use, which is equal to the gross inflow less the committed water
Water productivity (WP)	Physical mass of production (rice) measured against irrigation inflow ($WP_{irrigation}$), gross inflow (WP_{gross}), net inflow (WP_{net}), process-depleted water ($WP_{ET\ (rice)}$), or available water ($WP_{available}$)
Depleted fraction (DF)	Fraction of gross inflow (DF_{gross}) or available water ($DF_{available}$) that is depleted by process and non-process uses (i.e., rice evapotranspiration and non-rice evapotranspiration, respectively)
Process fraction (PF)	Process depletion (in this case, rice evapotranspiration) divided by gross inflow (PF_{gross}), or ($PF_{depleted}$), available water ($PF_{available}$)

canal commands of the West Main Canal and First Main Canal are relatively small, hence these two canal commands are considered as one. The Second Main Canal and Third Main Canal command area, including the Tuanlin pilot area, are considered separately.

Detailed maps that indicated the canal command boundaries were not available. To define these boundaries, a combination of a digital elevation model (resolution 1 km), the panchromatic band of Landsat 7 ETM+ of 10 July 2000 (resolution 15 m), and topographic maps, including the canal layout, were used. The main canal command scale includes the cultural (irrigated) command area of a canal system plus significant non-agricultural land cover including forest, urban areas, water bodies, and roads.

Meso scale

The two sites representing this scale are the Tuanlin and Wenjiaxiang pilot areas (see also Dong 2004 in this journal). The Tuanlin pilot area represents a situation where ISI is widely practiced and is irrigated by the first branch of the Third Main Canal and a small-sized reservoir upstream. The total area is 287 ha, of which 41% are paddy fields. The Wenjiaxiang pilot area represents a situation where ISI is not so common and is supplied by the east branch of the Fourth Main Canal and is located at the tail-end of the canal. The total area is 606 ha, of which 28% are paddy fields. The northern part of the area is hilly and the elevation decreases gradually from north to south. The landscape of the pilot areas consists of rice fields, trees, villages, roads, canals, drains, and many storage ponds. The main crop at the two sites is middle rice that grows from the end of May to early September. Upland crops, such as maize and soybean, are also planted during the middle rice-growing season but are normally not irrigated.

Water management practices and processes at this scale include allocation and distribution of water to fields, control of canal seepage, rainfall, runoff, and storage. Other non-agricultural uses influence overall water use. Within the meso scale, there is ample opportunity for reuse, but surface drainage outflow from the area also occurs. Downstream of the pilot areas are medium-sized reservoirs that capture all drainage flows. The source of water for the reservoir is the non-irrigated land that acts as a catchment area for the reservoir, plus any drainage water from rice fields. The reservoir is a supply for downstream agriculture plus cities and industries.

Field scale

To represent this scale, three rice fields were selected in each of the two pilot areas, Tuanlin (ISI) and Wenjiaxiang (non-ISI), to capture the differences between on-farm irrigation water use of fields with and without ISI. The three plots were in the high, middle and low of the topographical sequence.

Water accounting

The water-accounting procedure developed by IWMI (Molden 1997; Molden and Sakthivadivel 1999), based on a water balance approach, was applied to study water savings. The water-accounting procedure classifies water balance components based on the (surface) outflow and on how the water is used. The water-accounting system was considered at the four spatial scales chosen to capture the upscaling effects of field-scale interventions. The water-accounting indicators are presented in the form of fractions and in terms of productivity of water and are explained in Table 1.

At the field scale, the time period for water accounting was from land preparation (20 May 2000) up to the end of harvesting (31 August 2000). In the six pilot fields, rice transplanting took about 3 days in the period of 22–30 May 2000. At the meso scale, the time period for water accounting was from land preparation (20 May 2000) up to the end of harvesting (10 September 2000). At the main canal command area and subbasin scale, the time period for water accounting was from 15 April to 15 September 2000 for evapotranspiration. For irrigation releases for the main canal commands, the period was from 1 April to 1 September 2000, since only monthly data were available for all the main canals. However, as daily data for the general main canal, first main canal, and west main canal show, no irrigation water releases occurred before 10 April 2000 and after 1 September 2000. For rainfall, the period of 1 May to 10 September 2000 was used.

Measurements

Land-use pattern

At the field scale, only rice plots were selected and the area of the fields was measured. At the meso scale, the land-use pattern was determined using secondary data from the villages in the area. Rice and non-rice areas were distinguished by applying remote sensing techniques, but was only partly successful due to the small size of the fields.

At the main canal command area and subbasin scale, rice and non-rice areas were distinguished by applying remote sensing techniques. The satellite image of 10 July 2000 (Landsat 7 ETM+) was used for this classification purpose. However, the Landsat 7 ETM+ (thermal band resolution 30 m) was unable to capture field canals, field roads, and rice field bunds. Therefore, a correction factor was applied to the rice area. A percentage of 5% for field canals, 5% for rice field bunds, and 4% for field roads is subtracted from the total area classified as rice.

Evapotranspiration

At the field and meso scale, the reference evapotranspiration (ET_0) was calculated with the Penman-Monteith equation (Allen et al. 1998). All meteorological data for the ET_0 calculation came from the Tuanlin Irrigation Experiment Station. The meteorological factors were manually observed three times per day (at 0800, 1400,

and 2000). Daily data was used as input for the ET_0 calculations. The actual evapotranspiration was calculated by multiplying the ET_0 by a crop coefficient (provided by Mao 1992). This method assumes no water stress during the crop growing season, which was verified with field level measurements of standing water on the field and with remote sensing data in the meso scale. The evaporation from open water (ponds, canals) was calculated with pan-evaporation data from the Tuanlin Irrigation Experiment Station.

At the main canal command and subbasin scales, the actual evapotranspiration was estimated with the surface energy balance algorithm for land (SEBAL) developed by Bastiaanssen et al. (1998). SEBAL is a thermodynamically based model, seeking to find energy-balance terms at the land surface. The practical procedures are extensively described in Chemin and Ahmad (2000) and Tasumi et al. (2000). Chemin and Alexandridis (2001) describe in detail the procedure on how the actual evapotranspiration is calculated from NOAA AVHRR images acquired at various dates in the ZID. The result is a grid cell map of actual evapotranspiration during the rice growing season, which was merged with a Landsat 7 ETM+ image (image acquired on 10 July 2000) to redistribute the seasonal evapotranspiration to finer resolutions to provide an improved local estimation of water consumption. A correction factor was applied to the evapotranspiration from rice, to correct for the non-rice evapotranspiration areas classified as rice. A percentage of 5% for field canals and 5% for bunds is subtracted from the total evapotranspiration in the rice area and is then replaced by the corresponding actual evapotranspiration of non-rice calculated with the SEBAL in the canal command area. Field roads are assumed to be bare soil and 4% of the total evapotranspiration in the rice area was subtracted and then substituted by the corresponding evaporation of bare soil calculated with the SEBAL in the canal command. To validate the remote-sensing evapotranspiration data, a comparison was made between ET derived from remote sensing at the meso scale and ET derived from climatological data from the Tuanlin Irrigation Experiment Station. Remote sensing method underestimated the evapotranspiration from rice by 3% over the rice growing season compared to evapotranspiration derived from the climatological data

Rainfall

For the field and meso scale, rainfall measurements were taken daily in both Tuanlin and Wenjiaxiang. For the main canal command and subbasin scale, monthly rainfall data from 23 stations were used. A representative area was attributed to each station by applying the Thiessen polygon method. The volume of rainfall was calculated by multiplying the representative area by the rainfall. Since none of the stations were located close to the boundary of the subbasin scale, the area attributed to the stations just inside the boundary was large, and might lead to less accurate rainfall volume. Compared with the World Water and Climate Atlas (IWMI 2000), which uses 30 years of data, the 2000 rice growing season was a rice growing season with average rainfall in ZIS.

Surface water inflow and outflow

Inflow and outflow of surface water were measured at the boundaries of the study area (at both the field and meso scale) twice a day. The discharge was measured mainly with broad-crested weirs, additionally v-notch weirs and pipes were used. In the main and branch canals, a current meter was used for the discharge measurements. The operating time of several pump stations was recorded for discharge calculations. Water volume is calculated by multiplying the discharge by time. At the main canal command and subbasin scales, secondary data from the Zhanghe Administrative Bureau on water releases to the main canals and from the Zhanghe reservoir (considered as surface inflow) were collected. Additionally time series data for the Zhanghe reservoir releases were collected (Loeve et al. 2004) and the data were found to be consistent. However there is some discrepancy between reservoir releases and added volumes of the separate canals. Most likely the irrigation releases for the separate canals are under estimated.

Water storage change

Storage change at field and meso scale was calculated for (1) soil moisture: before land preparation and after harvesting the soil moisture content in the top 30 cm of the soil was measured by the gravimetric method; (2) surface storage: before land preparation and after harvesting water levels in selected ponds were measured and multiplied by the total area covered by the ponds; and (3) groundwater: before land preparation and after harvesting the water levels in four wells in each meso site were measured. The groundwater volume was calculated by multiplying the water level by the specific yield of the soil (estimated specific yield 0.10).

Water levels in fields

The water levels in the selected fields were measured to assess whether ISI was prevalent in an area.

Yield

For the field scale, yield data were obtained from a crop cut of 6 m^2 in the field. For the meso scale, yield data were obtained from a socioeconomic survey with a sample size of 30 spread over the meso sites. For the main canal command and subbasin scale, remote sensing was used to calculate rice yield. By applying the method described in Bastiaanssen and Ali (2003), a biomass growth map was produced from NOAA images, after which the spatial resolution was improved with a Landsat 7 ETM+ image. The non-rice areas were masked out by using the land-use map mentioned above. Same as for rice area and evapotranspiration, a correction factor was applied to the biomass production in the rice area. A percentage of 5% for field canals, 5% for bunds and 4% for field roads is subtracted from the total biomass production in the rice area. A harvest index value of 0.5 was used for biomass to rice production conversion, which is very much in line with the later findings of Belder et al. (2004) of an average harvest index of 0.52 after extensive field trials. Rice production divided by rice area results in yield. To validate the remote-sensing yield data, a comparison was made between yield derived from remote sensing on the meso scale and from the socioeconomic survey. The results were very comparable with a rice yield estimate from the socioeconomic survey of 6,330 kg ha^{-1} while RS data indicated a yield of 6,120 kg ha^{-1}, i.e., only an underestimation of 3%.

Results

Table 2 summarizes results across scales. The following discussion of results presents each indicator and discusses how and why they change across scale.

Total area and rice area

While rice is the dominant crop in ZIS, it does not cover the entire landscape, covering approximately 27% of the area at the subbasin scale. At the field scale, rice is of course almost 100% of the area. This is one of the major factors that will influence the differences in water accounting indicators across scales.

Table 2 Water-accounting indicators on different scales

Descriptors	Scales					
	Measurements		Remote sensing			
	Field[a]	Meso[b]	First main canal command[c]	Second main canal command	Third main canal command	Subbasin (ZID)
Total area (ha)	0.76	287	28,519	160,206	196,388	466,800
Rice area (% of total)	98	41	19	28	32	27
Irrigation (mm)[d]	493	776[e]	263	182	202	241
Irrigation (m^3) (000)	3.4	905[e]	14,140	81,266	125,592	303,275[f]
Rainfall (mm)	463	463	469	471	326	378
Rainfall (m^3) (000)	3.5	1,328	133,886	754,194	639,427	1,763,290
Gross inflow (mm)[g]	956	5,099	519	521	390	443
Gross inflow (m^3) (000)	6.9	14,630	148,026	835,461	765,019	2,066,564
Committed outflow (mm)	0	4,055	Unknown	Unknown	Unknown	Unknown
Committed outflow (m^3) (000)	0	11,634	0[h]	0[h]	0[h]	0[h]
Available water (mm)[g]	938	1040	519	521	390	443
Available water (m^3) (000)	6.8	2,983	148,026	835,461	765,019	2,066,564
ET (rice) (mm)	623	635	494	529	522	510
ET (rice) (m^3) (000)	4.6	741	26,539	235,804	324,092	642,749
ET (non-rice) (mm)	0	374	316	395	362	337
ET (non-rice) (m^3) (000)	0	637	73,225	456,642	486,396	1,146,768
Total depleted (mm)[g]	623	480	350	432	413	383
Total depleted (m^3) (000)	4.6	1,378	99,764	692,446	810,488	1,789,517
Production (t)	5.6	739	24,780	242,373	333,820	663,705
Yield (kg ha^{-1})	7427	6330	4612	5437	5379	5264
Indicators						
WP gross (kg m^{-3})	0.67	0.05	0.17	0.29	0.44	0.32
WP irrigation (kg m^{-3})	1.65	0.82	1.75	2.98	2.66	2.19
WP ET(rice) (kg m^{-3})	1.19	1.00	0.93	1.03	1.03	1.03
PF gross (rice)	0.67	0.05	0.18	0.28	0.42	0.31
PF available (rice)	0.69	0.25	0.18	0.28	0.42	0.31
PF depleted (rice)	1.00	0.54	0.27	0.34	0.40	0.36
DF gross	0.67	0.09	0.67	0.83	1.06	0.87
DF available	0.69	0.46	0.67	0.83	1.06	0.87

[a] Tuanlin 2000, average of three field sites
[b] Tuanlin meso site, 2000. Adjusted from Dong et al. (2001)
[c] The first main canal command is the aggregation of the First Main Canal and West Main Canal command
[d] Assuming only rice is irrigated. ZIS water only, except for field scale where no differentiation between sources could be made
[e] The volume of irrigation water is adjusted for the enormous amount of committed water flowing through the meso site. The irrigation diversion flowing into the area is a factor 10 bigger than the irrigation water available for the area
[f] The added values of all canals should be the same as the total release from Zhanghe reservoir, however this calculation yields only 250,268 thousand m^3. Most likely the irrigation releases for the separate canals are under estimated
[g] To convert to millimeters, the cubic meters are divided by total area
[h] The committed outflow for the main canals is unknown, but the irrigation water diversions are meant for agricultural use within the canal command, hence, the committed outflow is set to zero for further calculations

Irrigation and rain supplies

We considered the ZIS reservoir as the main irrigation supply. In fact, farmers use a number of sources of irrigation water, some of which originates from the ZIS reservoir and another portion derived from runoff generated within the command area and stored in ponds, drains, or reservoirs. At field scale, we consider irrigation from any source. At larger scales, we used canal measurements to represent the amount of water from the Zhanghe reservoir. At the meso scale, a supply canal passed through the study area domain so the irrigation inflow was high, but also the measured committed outflow for downstream use. Only irrigation water from the Zhanghe reservoir (measured supply canal inflow minus measured supply canal outflow) was taken into account to calculate water productivity per unit of irrigation water. The first, second and third main canal all had smaller irrigation duties (in mm) than the field and meso level. But each canal was

different, representing a response by the main canal operators to differing irrigation needs.

Management and utilization of rainfall using different strategies across scales, is extremely important at ZIS. Rainfall varied across the command area, with the 3rd main canal receiving less rain during the season. As described in Dong et al. (2004, this volume), ISI practices allow capture of rain because farmers use high bunds and keep the water level on their fields low. Additionally, runoff from rainfall on non-rice land is captured through ponds and reservoirs in the command area. In Tuanlin farmers apply about 493 mm irrigation water to their fields, and the average water depth applied from the Zhanghe reservoir is 241 mm, farmers get at least 242 mm, exactly half of their water from irrigation sources where water is generated from rain within the ZIS area. This is very much in line with data for the third main canal command, which also indicates that in the period 1979–1998 about 50% of the total water resources come

from sources within the third main canal command (Loeve et al. 2001).

Gross inflow (rain plus surface sources into the domain)

Gross inflow at the field scale represents farmer practices—the sum of surface flows into the domain plus rain. This shows a jump at the meso scale because of the large canal passing through the area. It declines markedly at larger scales, because ZIS operators only need to supply part of the water supply to farmers. Farmers require about 960 mm of rain plus irrigation water in the rice growing season, about 50% is met by rain directly on the field, 25% from the Zhanghe reservoir water, and an additional 25% from internal water sources.

Committed outflow

This represents the amount of water required for downstream uses. At the field scale, we set committed outflow to 0, meaning that farmers could capture and deplete all the water. At the meso scale, the measured canal outflow is considered as the committed water need for downstream uses. This is an enormous amount for the meso scale because the irrigation diversion flowing into the area is a factor 10 times bigger than the irrigation water available for the area. Regarding the Chenghu Lake, a dominant feature of the landscape is situated downstream of ZIS, and must be partly dependent on flows from the ZIS areas. We did not find any estimates of environmental flow requirements to this lake, nor did we make an estimate. Furthermore the irrigation water diversions are meant for agricultural use and not for environmental flow requirements. Hence, the committed outflow for the main canals is set to zero for further calculations. However if drainage surface outflow declines to the lake, this must surely be an environmental issue of concern that should be addressed.

Available water (gross inflow less committed water)

This represents the amount of water that could be used within the domain. At the field scale, we set available water equal to gross inflow, while at the meso scale, the available water is the gross inflow minus the measured canal water flowing downstream.

Evapotranspiration

Assuming water is not a limiting factor in rice production, rice evapotranspiration should be scale independent. At the field and meso scale, rice evapotranspiration was estimated using the Penman Monteith method and results of about 625 mm were obtained; while at the main canal and subbasin scales remote sensing was used, and results of about 520 mm were obtained. Comparing the rice evapotranspiration data with rice yield at the different scales showed that the Tuanlin area also obtained a higher yield than the average in ZID, and rice evapotranspiration per kg rice production remained almost the same over scale. The average non-rice landscapes (trees, villages, ponds) showed evapotranspiration values of approximately 2/3 of the well-watered rice areas.

Rice yield

Rice yield had the highest value within the Tuanlin meso area. Evidently there was variability in yield, with some farmers receiving much lower yields.

Water-accounting indicator trends over scale

The following figures illustrate the trends over scale of water productivity (Fig. 1), process fraction (Fig. 2), and depleted fraction (Fig. 3). To ensure that all scales are visible, a logarithmic scale was chosen for the area. However, this presentation has the limitation that the relative differences between scales (1–1,000 ha looks the same as 1,000–1,000,000 ha) are less obvious. For the meso scale, only the Tuanlin pilot area (ISI) was included and for the main canal command scale, only the Third Main Canal command was incorporated into the graphs, since this is the canal command where the Tuanlin meso site is located.

The water productivity trend over scale (Fig. 1) shows that the water productivity per unit of rice evapotranspiration (WP ET_{rice}) stays just above 1 kg m^{-3} over all scales; which implies that the rice plant still needs the same amount of transpiration for production regardless of the amount of water applied.

The water productivity per unit of gross inflow (WP $gross_{rice}$) drops dramatically at the meso scale because of considerable (drainage) surface outflow from the domain. However, this outflow is captured again at the Third Main Canal command scale and the value rises again. At the subbasin scale, there is a small drop again, because other factors become important, such as runoff capturing of the natural vegetation. Because of lateral flows across scale domain boundaries, and recapture of this flow, the water productivity of gross inflow is scale-dependent.

The water productivity per unit of irrigation water (WP $irrigation_{rice}$) is very high at the field scale because farmers are extremely cautious with limited supplies, and there is an indication that they are sensitive to the price they have to pay. It decreases at the meso scale because of drainage out of the area and increases dramatically at the Third Main Canal command scale because of the capture of internally generated water plus reuse. This shows that a large enough spatial scale is needed to have an effect from the reuse of water. At the subbasin scale, there is a slight decrease, but the value is much higher than at the field scale.
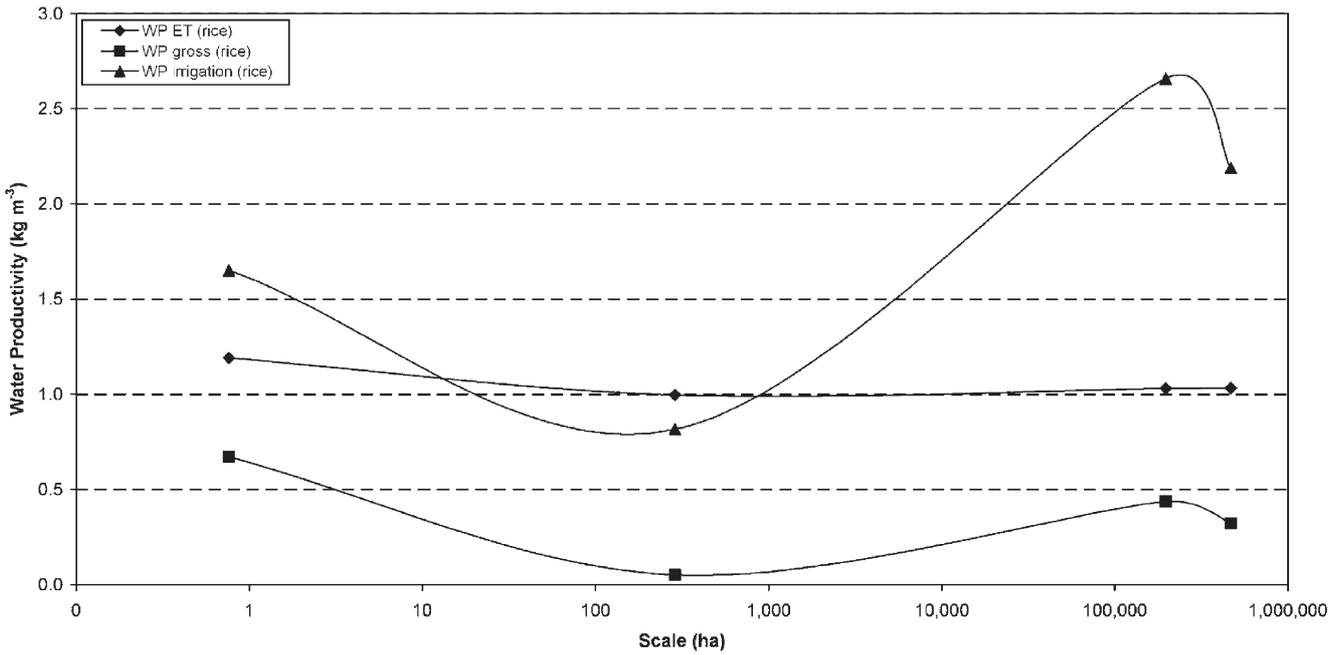
Fig. 1 Trends of water productivity (WP) per unit of gross inflow, irrigation inflow, and evapotranspiration over scale
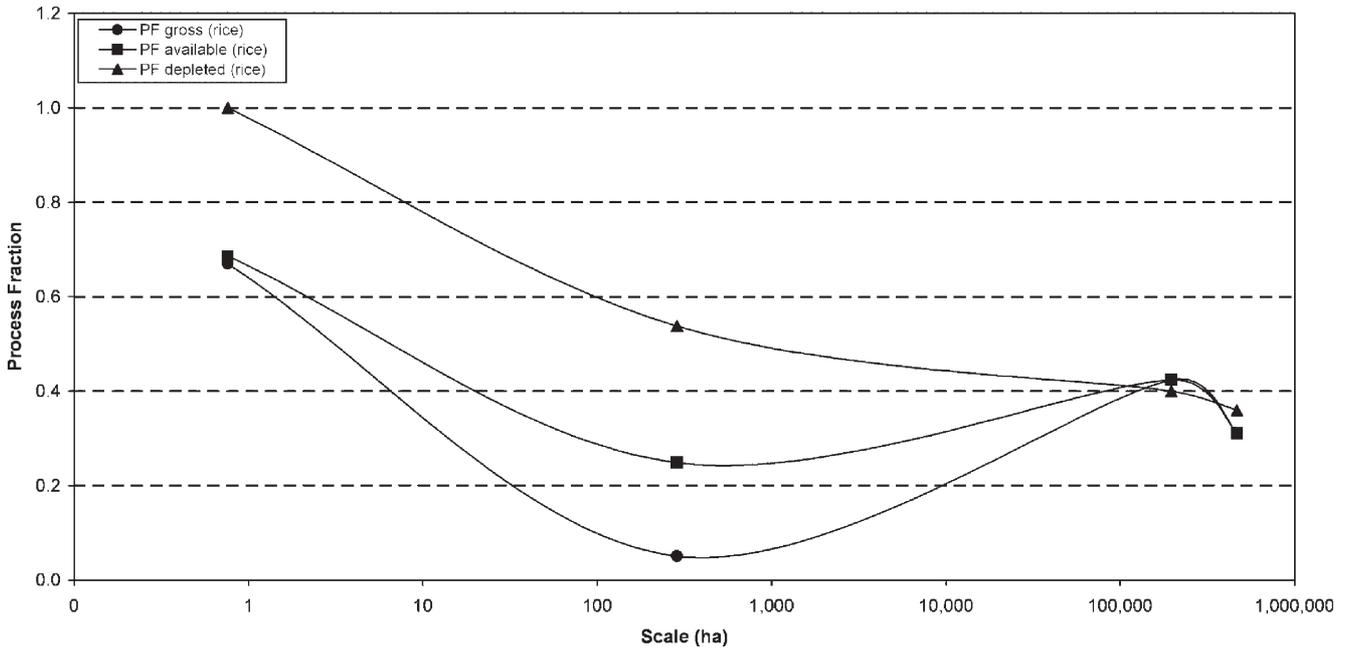

Fig. 2 Trends of process fraction (PF) per unit of gross inflow, available water, and depleted water over scale

The process fraction per unit of gross inflow (PF gross in Fig. 2) at the field scale is very high, indicating that farmers have made much effort to make full use of irrigation water and rainfall. At the meso scale, the value of the process fraction per gross inflow drops dramatically to 5%. This is explained by the huge amount of measured surface inflow and outflow, which is used again at the main canal command scale. Because of runoff capture and reuse, the process fraction of gross inflow increases again at larger scales. At the subbasin scale, a slight decrease occurs, which is in line with a slightly lower percentage of rice land use at this scale. The process fraction per unit of depleted water (PF depleted) shows a downward trend going up the scales. Other land uses such as upland crops and non-cropped areas gain more importance when the scale becomes larger.

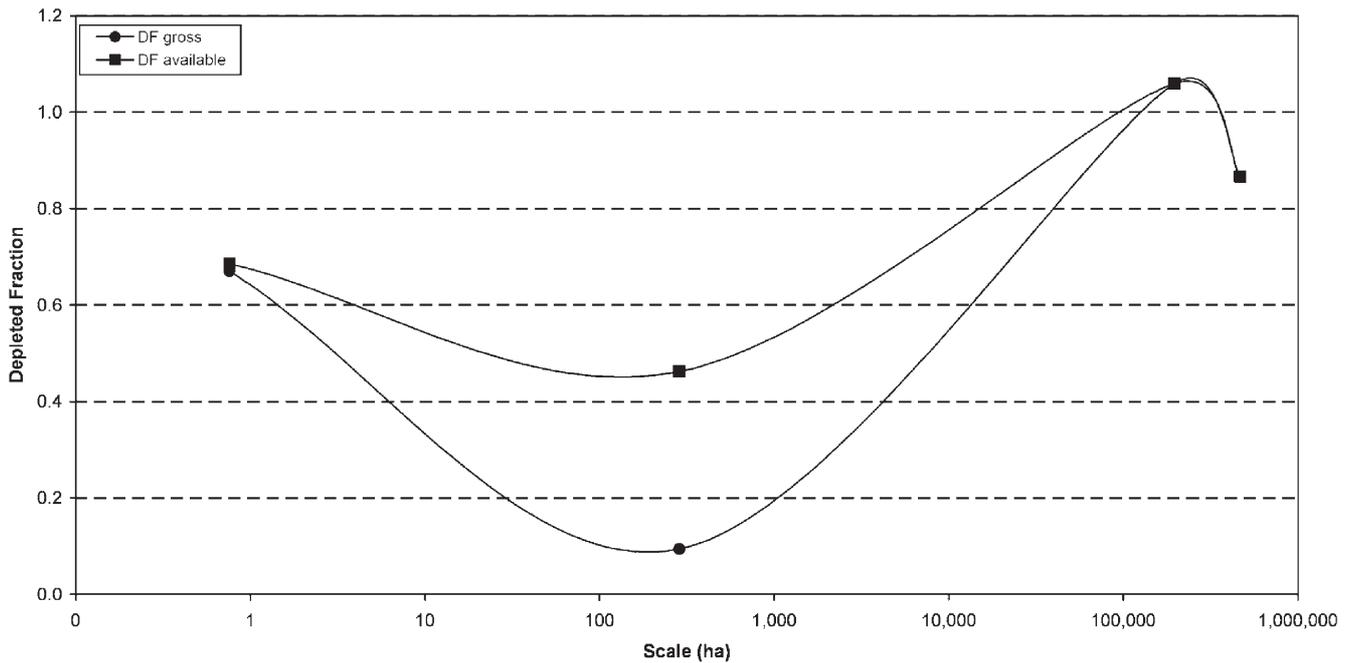The depleted fraction of gross inflow trend over scale (DF$_{gross}$ in Fig. 3) again shows a downward trend from the

Fig. 3 Trends of depleted fraction (DF) per unit of gross inflow and available water over scale

field scale, where farmers are quite effective in capturing and storing rain, to the meso scale, where much outflow reduces the DF_{gross} value. At the Third Main Canal command scale, DF_{gross} increased enormously. It is striking that values close to 1.0 are achieved, meaning that farmers and water managers are extremely effective in capturing and depleting the water available to them. Most water is depleted within the area and not much outflow will be available for downstream use. A high value for the depleted fraction is often a danger sign for the environment. At the subbasin scale, the depleted fraction per unit of gross inflow decreases. There is not much scope for additional savings in the area by converting drainage surface outflow to more process depletion.

Discussion and conclusions

Although different crops are grown in ZID, and especially when looking at the larger basin scale land, uses other than rice become important; water productivity parameters were calculated for rice only. The main reason for this being that paddy fields are occupying about 80% of the total irrigation area to which water is diverted.

Results from the Tuanlin Irrigation Experiment Station and actual farmer practices show that water-saving irrigation techniques such as Intermittent Submerged Irrigation reduce water deliveries to fields without significantly changing yield. Thus, water productivity per unit of water delivered to the fields is higher with ISI than with conventional practices. At field scale, the process fraction of gross inflow is very high and indicates that much effort has been made to make full use of irrigation water and

rainfall. Field observations indicate that farmers are quite effective in capturing and storing rain, even with traditional practices. This demonstrates that the practice of ISI is particularly valuable for farmers when coping with water scarcity. But how does this "scale up", and does the practice lead to real basin scale water savings?

The study clearly demonstrates the high dependence to the scale of water use and productivity parameters. Depleted fraction and water productivity per unit of supply varied dramatically across scale. Thus, it is not possible to conclude from field scale observations that basin level water savings will or will not take place.

The major reasons for these scale effects are the lateral flow of water across boundaries, differing land use patterns across scales, and changing water management patterns across scales. Drainage surface outflow across boundaries of the meso scale was captured and reused at a larger scale, thus the depleted fraction was lower at meso scale and higher at larger scale. In contrast, water productivity per unit of evapotranspiration showed little scale dependence, because the ET water flux is vertical and the water cannot be recaptured within ZIS. The land use pattern at the field scale was paddy fields only, while at the meso and larger scales the entire landscape was considered including forest land, villages, and importantly ponds. Rainfall, runoff capture, and recapture of drainage flows play a very important role at larger scales.

While the focus of the study was on ISI practice, it later became clear that management of rainwater was extremely important in overall water resource management, and different strategies played a role at different scales. At the field scale, farmers tried to store as much rainwater as possible in their bunds. ISI practices facilitated rainfall capture and storage because farmers could

keep lower ponding levels. At larger scales a dense array of small-sized ponds to medium-sized reservoirs captured internally generated runoff. This additional storage and reuse pushed values of depleted fraction and water productivity per unit of Zhanghe reservoir water higher at larger scales. This internal storage gave farmers other sources of water and more flexibility in their farm operations. It is not uncommon that farmers have a choice of two or three sources of water: Zhanghe reservoir water, water from small ponds, or water from drains.

Is there a possibility for additional water savings? All indicators show a decrease when scaling up from the main canal command scale to the subbasin scale. Other land uses such as upland crops and non-cropped areas gain even more importance at this scale. This also becomes very clear in the trend of the process fraction per unit of depleted water, which shows a continuous downward trend going up the scales. At the sub-basin scale encompassing Zhanghe Irrigation District, including irrigated and non-irrigated areas, the depleted fraction of gross inflow (evapotranspiration from all land uses divided by rain plus Zhanghe reservoir water supplies) is 0.87. Only 13% of the gross inflow (Zhanghe reservoir releases and rainfall) is flowing out of the Zhanghe Irrigation District. This is remarkable in light of common claims that irrigation is 40% efficient, and paddy irrigation extremely wasteful of water. This result shows exactly the opposite; agricultural water management practices at ZIS are extremely effective at converting water supplies from rivers and rainfall into evapotranspiration, and little or no water is wasted. It is true that only 36% of depleted water within ZIS is evapotranspired by rice, and the rest by other land use cover (including upland crops). There may be a possibility of changing land use to yield more water for rice, for example forest to rice, but whether this is desirable would require much more investigation and discussion.

It is important to put this into an overall basin perspective. The Yangtze basin is considered to be an "open basin" in that not all water is allocated, and there is a relatively large discharge flowing out of the basin to the sea. Downstream users would not be adversely affected by more depletion in the ZID, and probably would not "feel" decreases or increases in Yangtze River flows caused by changes in ZIS management. This is in contrast to the Yellow River where additional depletion by upstream users would be felt by downstream users. But water savings at Zhanghe can be used within the area to serve Zhanghe users—hydropower, cities, industries and agriculture. With only 13% of the rainfall and irrigation water releases flowing out of the basin, it is expected that the surface outflow cannot be further exploited without negative downstream effects on, for example, Chenghu Lake.

The main scope for improvement lies in increasing the water productivity within ZIS. One way is for higher yields at the same level of basin water depletion, e.g. with help of new crop varieties or improved irrigation scheduling. In a broad sense, increasing productivity of water equates to obtaining more value from the water depleted in the area. Thus, a second way of increasing water productivity is through internal reallocations that yield more benefit per unit of water, for example reallocating to higher valued crops, or reallocation to higher valued city or industrial uses. This has in fact been happening over time, with more water from the reservoir diverted to hydropower and cities (Loeve et al. 2004), and agriculture adjusting via more reliance on local small pond sources. On-farm water management practices such as ISI have an important role to play in allowing water to be kept in storage high in the system, allowing more flexibility on where water should be used later.

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