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Field-level water savings in the Zhanghe Irrigation System and the impact at the system level

R. Loeve, B. Dong, and D. Molden

The demand for freshwater from cities, industries, and environmental uses is growing rapidly throughout Asia. Less water will be available for agriculture and for rice in most places, yet more rice will be needed to feed a growing population. The per capita freshwater availability in China is among the lowest in Asia and it is becoming increasingly difficult to develop new freshwater sources. Much of the water will have to come from water savings—and rice, a water-intensive crop, is a major target for such savings.

On-farm water-saving practices, such as alternate wet and dry irrigation (AWDI), have been developed to reduce irrigation application requirements and to improve growing conditions, thereby increasing yield. However, the question is, If these practices have led to "real" water savings, which can be transferred to other agricultural and nonagricultural uses?

This paper explores water savings and water productivity on different scales to see if and how field-scale interventions scale up to subbasin-scale water savings in the Zhanghe Irrigation District (ZID) in Hubei Province, Central China. To study water savings and effects on different scales, the water-accounting procedure developed by IWMI was considered at four different spatial scales ranging from field to ZID.

Results show that at the field level, the water productivity per unit of irrigation water was much higher under AWDI than under the traditional methods because of lower irrigation water input. Farmers put much effort into making full use of irrigation water and rainfall.

Moving up the scales, other land uses gain more importance. Apparently, a certain size of scale is needed to have an impact from reuse of water, which becomes evident only at the main canal command scale, where the water productivity per unit of irrigation increased dramatically and almost all water is used within the domain. It becomes clear that the ZID, with its possibilities of capturing rainfall and runoff in all the reservoirs with the system, is very effective in capturing and using water for productive use.

The scope for additional real water savings in the Zhanghe Irrigation District is limited. Only 12% of the combined rainfall and irrigation water releases flow out of the basin. A further reduction in drainage outflow from the ZID may have negative downstream effects.

The results clearly indicate that scale effects are important for understanding and planning for water savings and water productivity.

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. Yet, more rice will be needed to feed a growing population. The per capita freshwater availability in China is among the lowest in Asia 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, is a major target for such savings.

Major efforts have already been made to save water in irrigated rice areas and there is much to learn from previous efforts, particularly in China, where research and practices are well advanced. Many practices have been developed for farmers to deliver less water to their fields and these are collectively known as water-saving irrigation practices (Wang 1992, Mao 1993, Peng et al 1997), such as alternate wet and dry irrigation (AWDI), which has spread in South China (Li et al 1999). This practice is being implemented on a large scale in the Zhanghe Irrigation System (ZIS). A question of global interest is whether this practice has led to "real" water savings that can be transferred to other agricultural and nonagricultural uses.

The objectives of this paper are to (1) quantify the water productivity under AWDI and non-AWDI practices and (2) 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 extensively 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 apply less water. At the farm level, "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 nonagricultural uses—the environment, cities, and industries. In these situations, irrigated rice agriculture is a relatively low-valued use of water and there is pressure to meet other demands first and then let agriculture have the remaining water. At the basin scale, a common 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.

However, water-saving practices at the field scale, with the objective of reducing supplies to fields, do not necessarily lead to transferable savings at the basin scale. At the basin scale, factors such as recycling of water (especially where rice is a major crop) and interaction of nonagricultural uses with water use for rice play a major role. For this research, four different scales were selected: field scale, mezzo scale, main canal command scale, and subbasin scale.

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 ZIS is one of the typical large-size irrigation systems in China, with a total area of 5,540 km^2, of which about 160,000 ha are irrigated area.

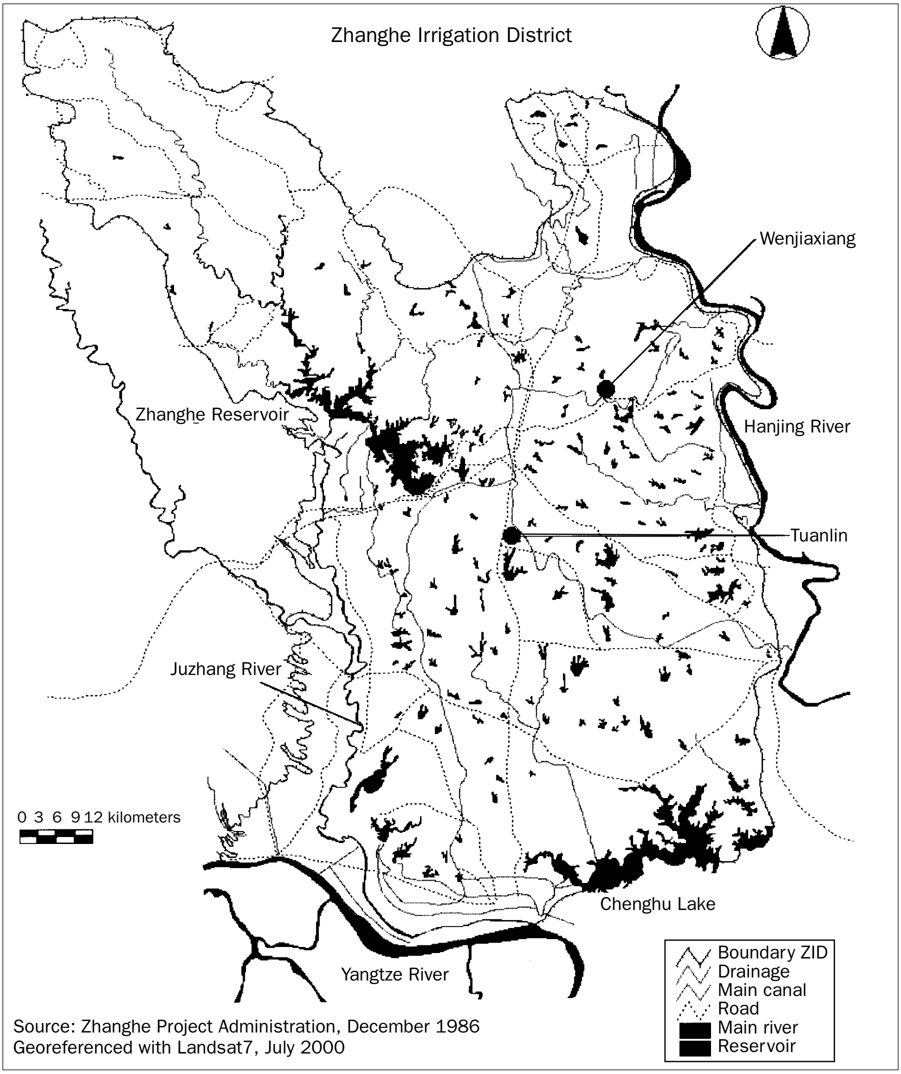
The Zhanghe reservoir, built on a tributary of the Yangtze River, supplies most of the irrigation water to the ZIS. The reservoir was designed for multipurpose uses of irrigation, flood control, domestic water supply, industrial use, and hydropower generation. In the ZIS, the canal systems include one general main canal, five main canals, and many branch canals with a total length of more than 7,000 km and more than 15,000 structures. Besides these, there are tens of thousands of medium- or small-sized reservoirs, small basins, and pump 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. Figure 1 shows a layout of the ZIS within the ZID. For the research, the ZID is considered as 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 canal commands of the west main canal and first main canal are relatively small and both canal commands are considered as one. The second main canal and third main canal command area, including the Tuanlin pilot area, are considered separately.

No detailed maps were available that indicated the canal command boundaries. To define these boundaries, a combination of a digital elevation model (resolution 1 km × 1 km), the panchromatic band of Landsat 7 ETM+ of 10 July 2000 (resolution 15 m × 15 m), and topographic maps, including the canal layout, were used. Obviously, the main canal command scale does not refer only to the cultural (irrigated) command area of a canal system.



Source: Zhanghe Project Administration, December 1986
Georeferenced with Landsat7, July 2000

Fig. 1. The Zhanghe Irrigation System within the Zhanghe Irrigation District.

Mezzo scale

The two sites representing this scale are the Tuanlin and Wenjiaxiang pilot areas. The Tuanlin pilot area represents a situation where AWDI is said to be widely practiced and is located about 20 km southeast of the Zhanghe reservoir (see Fig. 1). The Tuanlin pilot area 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 about 41% are paddy fields. The Wenjiaxiang pilot area represents a situation where AWDI is said to be not so common and is located about 35 km northeast of the Zhanghe reservoir (see Fig. 1). The Wenjiaxiang pilot area 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 about 28% are paddy fields. The northern part of the area is hilly and the elevation decreases gradually from north to south. 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 they are normally not irrigated.

The landscape of the pilot areas consists of rice fields, trees, villages, roads, canals, drains, and many storage ponds. Water management practices and processes at this scale include allocation and distribution of water to farms, control of canal seepage, rainfall, runoff, and storage. Other nonagricultural uses influence overall water use. Within the mezzo scale, there is ample opportunity for reuse, but drainage outflow from the area also occurs. Downstream of the pilot areas is a medium-sized reservoir that captures all drainage flows. The source of water for the reservoir is the nonirrigated 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.

Micro scale

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

Water accounting

The water-accounting procedure developed by IWMI (Molden 1997, Molden and Sakthivadivel 1999), based on a water balance approach, was used to study water savings. The water-accounting procedure classifies water balance components based on the outflow and on how the water is used. The water-accounting system was considered at the four spatial scales chosen to capture the scale 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 Box 1.

At the micro scale, the time period for water accounting was from land preparation (about 20 May) to 31 August. At the mezzo scale, the time period for water accounting was from land preparation (20 May) up to the end of harvesting (in 1999, 20 September, and in 2000, 10 September). At the main canal command area and subbasin scale, the time period for water accounting was from 15 April to 15 Septem-

Box 1. Water-accounting indicators and terminology (Molden 1997).

Gross inflow
The 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
The part of the outflow that is reserved for other uses such as downstream water rights or environmental uses.

Available water
The amount of water available to a service or use, which is equal to the inflow less the committed water.

Water productivity (WP)
The 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)
The fraction of gross inflow (DF_{gross}) or available water ($DF_{available}$) that is depleted by process and nonprocess uses (i.e., rice evapotranspiration and nonrice evapotranspiration, respectively).

Process fraction (PF)
The fraction of rice evapotranspiration over gross inflow (PF_{gross}), over total depletion ($PF_{depleted}$), and over available water ($PF_{available}$).

ber 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 micro scale, the selected fields were cultivating rice and the area of the fields was measured. At the mezzo scale, the land-use pattern was determined with secondary data from the villages in the area. The total area was determined from a map and with help from remote sensing. At the main canal command area and subbasin scale, a satellite image (Landsat 7 ETM+, 10 July 2000) was used to create a land-use classification map. However, since the rice fields in the ZIS are small, the Landsat 7 ETM+ resolution (30 × 30-m thermal band) will not 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 mezzo 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 were from the Tuanlin Irrigation Experiment Station. The meteorological data were manually observed thrice a day (at 0800, 1400, and 2000). Monthly averages were used as input for the ET_0 calculations. The actual evapotranspiration was calculated by multiplying the ET_0 by a crop coefficient. The evaporation from open water (ponds, canals) was calculated with pan-evaporation data from the Tuanlin Irrigation Experiment Station.

At the main canal command area and subbasin scale, the actual evaporation 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 and these images are used together with daily reference evapotranspiration data from the Tuanlin Irrigation Experiment Station. The result from the NOAA AVHRR images is a seasonal actual evapotranspiration map, which was merged with a Landsat 7 ETM+ image (image acquired on 10 July 2000) to redistribute the seasonal evapotranspiration to finer resolutions. The result is an improved local estimation of water consumption. However, since the rice fields in the ZIS are small, the Landsat 7 ETM+ resolution (30 × 30-m thermal band) will not capture field canals, field roads, and rice field bunds. Therefore, a correction factor was applied to the evapotranspiration from 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 area of evapotranspiration of natural vegetation observed in the canal command area when separating the evapotranspiration by land use. 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 equivalent area of bare soil evapotranspiration observed in the canal command. To validate the remote-sensing evapotranspiration data, a comparison was made between ET derived from remote sensing at the mezzo scale and ET derived from climatological data and land use at the mezzo scale. The results were very comparable and will be presented in Chemin et al (2002).

Rainfall. For the micro and mezzo 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 with help from Thyssen polygons. The volume of rainfall was calculated by multiplying the 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 the closest to the boundary was big. This might lead to less accurate rainfall volume data.

Surface water inflow and outflow. Inflow and outflow of surface water were measured at the boundaries of the study area (at both the micro and mezzo scale) twice a day. The discharge was measured using different measurement structures, such as broad-crested weirs, V-notch weirs, trapezoidal weirs, and pipes. In the main and branch canals, a current meter was used for the discharge measurements. In temporary inflow/outflow points, portable cutthroat flumes were installed. The operating time of several pump stations was recorded for discharge calculations. The discharge was converted to a water volume by multiplying the discharge by time. The volume divided by the area gives the inflow and outflow in millimeters. To calculate the irrigation duty (for rice) in millimeters for the mezzo scale, the volume of committed outflow (i.e., the part of the outflow that is committed to downstream uses) is subtracted from the total irrigation water inflow and divided by the rice area. At the main canal command area and subbasin scale, secondary data were collected on water releases to the main canals and from the Zhanghe reservoir.

Storage change. Storage change was calculated only in 2000 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 water 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 storage:* before land preparation and after harvesting, the water levels in four wells at each 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 AWDI was prevalent in an area. The water levels were monitored daily and measured in 1999 with an open-bottom lysimeter and a plastic tube; in 2000, the lysimeter was replaced with simple wooden sticks.

Yield. For the micro scale, yield data were obtained from a crop cut of 6 m^2 in the field. For the mezzo scale, yield data were obtained from a socioeconomic survey, which had a bigger sample size and better spatial distribution over the mezzo sites than the micro-scale yield data. For the main canal command and subbasin scale, remote sensing was used to calculate crop production. As described in Bastiaanssen and Ali (n.d.), a biomass growth map was produced from NOAA images. To improve the spatial distribution, a Landsat 7 ETM+ image was used. The nonrice areas were masked out using a land-use map. However, since the rice fields in the ZIS are small, the Landsat 7 ETM+ resolution (30 × 30-m thermal band) will not capture field canals, field roads, and rice field bunds. Therefore, a correction factor was applied to the biomass production in the rice area. A percentage of 5% for field canals and 5% for bunds is subtracted from the total biomass production in the rice area. Field roads are assumed to be bare soil and do not produce biomass. A harvest index value of 0.5 was used for biomass to rice production conversion. 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 mezzo scale and from the socioeconomic survey. The results were very comparable and will be presented in Chemin et al (2002). Secondary data on crop production were also collected at the subbasin scale.

Results

Table 1 shows the water-accounting indicators on different scales presented separately.

Micro scale

As presented in Dong et al (2001), results from the Tuanlin Irrigation Experiment Station show that the water productivity per unit of irrigation water under alternate wet and dry irrigation is significantly higher (average 27%) than under traditional irrigation methods. However, the yield difference between the two methods is not statistically significant.

The actual farmers' practices show similar results although none of the farmers we monitored practiced a pure form of AWDI or traditional irrigation. The field water-level measurements show that farmers in Tuanlin practiced a form of irrigation much closer to the ideal AWDI practiced in timing of irrigation application, application frequency, duration, and depth of water application than in Wenjiaxiang. The water productivity values per unit of irrigation water are higher (up to 34%) under AWDI than under traditional irrigation methods (Dong et al 2001). The average water productivity per unit of irrigation in Tuanlin is 1.64 kg m^{-3} (see Table 1). In 1999 and 2000, rice yields in Wenjiaxiang (non-AWDI) were slightly higher than those in Tuanlin (AWDI).

The process fraction of gross inflow (PF_{gross}) indicates the amount of gross inflow that is depleted by rice ET. At the field scale, PF_{gross} ranged from 0.66 to 0.93 at both sites, indicating 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.

Mezzo scale

In 1999, the irrigation duty in Tuanlin (AWDI) was 29% less and in 2000 about 21% less than in the Wenjiaxiang (non-AWDI) mezzo site. The water productivity per unit of irrigation was consistently higher for Tuanlin in both years. However, it is much lower than at the field scale. On average, rice consumes 55% of the depleted water ($PF_{depleted}$) in Tuanlin and 42% in Wenjiaxiang. Rice covers about 41% of the Tuanlin mezzo site and 28% of the area at Wenjiaxiang. At the mezzo scale, other land uses such as upland crops and noncropped areas (trees, houses, roads, canals, ponds) play an important role.

The depleted fraction of gross inflow ranges from 0.09 to 0.20 for the two mezzo sites (Table 2), much lower than at the field scale. Drainage flows out of the mezzo areas include runoff from nonrice land plus drainage flows from rice fields. What happens to these drainage flows?

Following the nondepleted water (the outflow) downstream of the mezzo sites revealed that the outflow was captured and stored in a downstream reservoir that again supplied water to agriculture, cities, and industries downstream. The mezzo site is a catchment area for downstream reservoirs situated within the ZID. The role of

Table 1. Water-accounting indicators on different scales. See Box 1 for explanation of WP, PF, and DF.

Descriptor	Scales					
	Measurements		Remote sensing			
	Field[a]	Mezzo[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 (ha)	0.74	117	5,373	44,577	62,060	126,086
Irrigation (mm)[d]	493	1,199	263	182	202	219
Irrigation (m^3) (000)	3.4	1,399[e]	14,140	81,266	125,592	275,729[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)	956	5,100	733	653	528	596
Gross inflow (m^3) (000)	6.9	14,630	148,026	835,461	765,019	2,039,019
Storage change (mm)	–18	–5	0	0	0	0
Storage change (m^3)	–140	–13,655	0	0	0	0
Net inflow (mm)	938	5,095	733	653	528	596
Net inflow (m^3) (000)	6.8	14,617	148,026	835,461	765,019	2,039,019
Committed outflow (mm)	0	4,55	0	0	0	0
Committed outflow (m^3) (000)	0	11,634	0	0	0	0
Available water (mm)	938	1,040	733	653	528	596
Available water (m^3) (000)	6.8	2,714	148,026	835,461	765,019	2,039,019
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

continued on next page

Table 1 continued.

Descriptor	Scales					
	Measurements		Remote sensing			
	Field[a]	Mezzo[b]	First main canal command[c]	Second main canal command	Third main canal command	Subbasin (ZID)
ET (nonrice) (mm)	0	374	316	395	362	337
ET (nonrice) (m^3) (000)	0	637[g]	73,225	456,642	486,396	1,146,768
Total depleted (mm)	623	1,010	810	924	884	847
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 (t ha^{-1})	7.4	6.3	4.6	5.4	5.4	5.3
Indicators						
WP gross (kg m^{-3})	0.81	0.05	0.17	0.29	0.44	0.33
WP net (kg m^{-3})	0.82	0.05	0.17	0.29	0.44	0.33
WP irrigation (kg m^{-3})	1.64	0.53	1.75	2.98	2.66	2.41
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	0.32
PF available (rice)	0.68	0.27	0.18	0.28	0.42	0.32
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	0.88
DF available	0.68	0.51	0.67	0.83	1.06	0.88

[a] Tuanlin, 2000, average of three micro sites. [b] Tuanlin mezzo site, 2000. Source 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. At the larger scales, only the releases from the main canals are taken into account and converted to application depth. Actual application depth will be higher because of reuse of water. [e] The volume of irrigation water is adjusted for the enormous amount of committed water flowing through the mezzo site. The irrigation diversion flowing into the area is a factor 10 bigger than the irrigation water available for the area. [f] The daily data on irrigation releases from the Zhanghe reservoir from 10 April 2000 (no earlier releases) to 1 September 2000 (no releases after) give a total volume of 301,184,562 m^3. The monthly values of all canals should add up to the total irrigation releases from the Zhanghe reservoir, but yields a volume of 250,273,156 m^3. The average number was used for further calculations. Possible reasons for this discrepancy are that the main canal administrations like to keep the total volume lower to pay less water fees to the Zhanghe reservoir, measurement inaccuracies, and seepage from the canal. [g] Of which nonbeneficial evapotranspiration (ET) is 412,451 m^3 and upland crop ET is 224,907 m^3.

Table 2. Water-accounting indictors at the mezzo scale in Tuanlin and Wenjiaxiang (Dong et al 2001). See Box 1 for explanation of DF, PF, and WP.

Indicators	Year 1999		Year 2000	
	Tuanlin	Wenjiaxiang	Tuanlin	Wenjiaxiang
DF_{gross}	0.13	0.20	0.09	0.20
PF_{gross}	0.09	0.08	0.05	0.08
$PF_{depleted}$	0.56	0.41	0.54	0.42
$WP_{irrigation}$ (kg m^{-3})	0.98	0.79	0.53	0.42
WP_{ET} (kg m^{-3})	1.04	1.72	1.00	1.01

these reservoirs within the ZID in capturing and reusing water should be reflected by the water-accounting indicators going up one scale to the main canal command scale.

Main canal command scale

Inflow into the main canal domain is either irrigation water releases from the Zhanghe reservoir or rainfall. It is assumed that there is no committed outflow from the main canal command scale since all irrigation water is specifically released for this particular command area. It is also assumed that, during the rice season, change in storage is small in comparison with other water-balance terms, and thus set at zero in our analysis. Therefore, gross inflow is equal to available water. Committed water to cities and industries is accounted for by the Zhanghe reservoir authorities, who label water releases as irrigation water or water for cities and industries.

As can be seen in Table 1, the water reuse on the main canal command scale is reflected in water productivity per unit of irrigation[1] values, which are three to almost six times as high as on the mezzo scale. However, to make a more accurate comparison between the scales, our Tuanlin mezzo site should be compared with the Third Main Canal command in which the Tuanlin mezzo site is located. Here we see that the water productivity per unit of irrigation is about five times as high as at the Tuanlin mezzo site. The marked increase across scales is because of the recapture and reuse of water by the reservoirs. At the mezzo scale, rainfall was not captured and entered the drain as runoff. At the larger scale, the rain was effectively captured and used.

The water productivity per unit of rice evapotranspiration remains almost the same (around 1 kg m^{-3}) since the rice plant still needs the same amount of water for production. There is some variability across space, but this indicator does not change across scale.

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[1] At this scale, we consider the Zhanghe reservoir releases only as irrigation water as this is the water that crosses the boundary of the domain.

The process fraction of gross inflow increased from the mezzo scale. However, the process fraction of depleted water decreased. Other land uses such as upland crops and noncropped areas deplete an increasing amount relative to process uses at this scale. In the third main canal command, about 32% of the total area consists of rice compared with 41% at the Tuanlin mezzo scale.

The depleted fraction of gross inflow increased enormously to a bit more than one in the third main canal command. This indicates that either the water storage decreased (be it groundwater abstraction or soil moisture depletion) and was used for water consumption or measurement errors occurred in the inflow. In spite of uncertainties in the estimate, this large value indicates that most water is depleted within the area and not much outflow will be available for downstream use.

The first and second canal commands also have fairly high depleted fractions of gross inflow, but some outflow still occurs that can be used downstream. The subbasin scale will show how much water ultimately is used within the Zhanghe Irrigation District.

Subbasin scale (Zhanghe Irrigation District)

The boundaries of the ZID scale are taken as the Zhanghe reservoir upstream, the Juzhang River to the west, the Yangtze River and Chenghu Lake to the south, and Hanjing River to the east. As for the main canal command scale, storage change and committed outflow are assumed to be zero. Table 1 shows the water indicators at the subbasin scale. The water productivity per unit of irrigation water is 2.41 kg m^{-3}, lower than that of the second and third main canal command, but higher than that of the first main canal command. Also compared with the weighted average value of the three main canal commands (2.73 kg m^{-3}), there is a decrease. However, there is some uncertainty about the actual volume of water released for irrigation. If the added monthly values of all canals are taken as the total irrigation releases from the Zhanghe reservoir (250.3 million m^3), the value of the water productivity per unit of irrigation water will be 2.65 kg m^{-3}. This is almost equal to the values on the third main canal command scale, but still slightly lower than the weighted average of the three main canal commands. The water productivity per unit evapotranspiration remains the same (around 1 kg m^{-3}).

The process fraction of gross inflow decreased slightly from 0.35 (weighted average of the three main canal commands) to 0.32. This means that 32% of the gross inflow is consumed by rice. This is very much in line with the small decrease in rice area at the subbasin scale. At the subbasin scale, the rice area is about 27% of the total area and in the three main canal commands the rice area is about 29% (weighted average) of the total area. The process fraction of depleted water went from 0.36 to 0.37 (weighted average of the three main canal commands). The depleted fraction decreased from 0.93 (weighted average of the three main canal commands) to 0.88. So, only 12% of the inflow (irrigation and rainfall) is flowing out of the Zhanghe Irrigation District.

Water-accounting indicator trends over scale

The following figures illustrate the trends over scale of water productivity (Fig. 2), process fraction (Fig. 3), and depleted fraction (Fig. 4). 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 to 1,000 ha looks the same as 1,000 to 1,000,000 ha) are less obvious. For the main canal command scale, only the third main canal command is incorporated since this is the canal command where the Tuanlin mezzo site is located.

The water productivity trend over scale (Fig. 2) shows that the water productivity per unit of evapotranspiration stays just above 1 kg m^{-3} over all scales; only the value at the field scale is a bit higher, for which we have no explanation. There may be location-specific differences in this value, but there is no reason to expect that this value is scale-dependent.

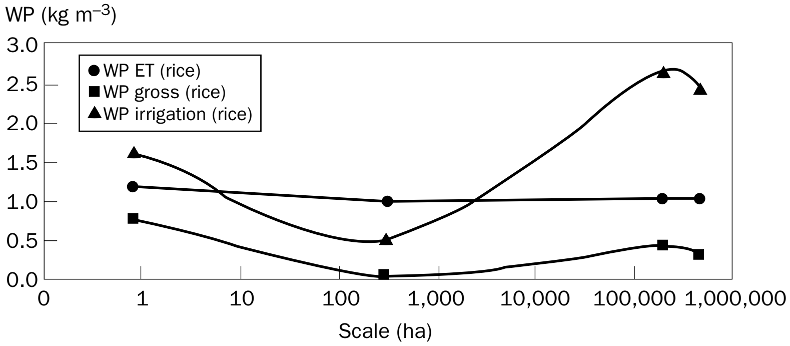

Fig. 2. Trends of water productivity (WP) per unit of gross inflow, irrigation inflow, and evapotranspiration over scale.

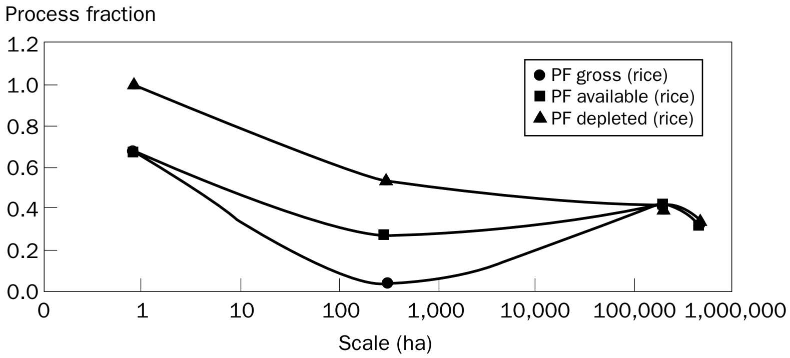

Fig. 3. Trends of process fraction (PF) per unit of gross inflow, available water, and depleted water over scale.

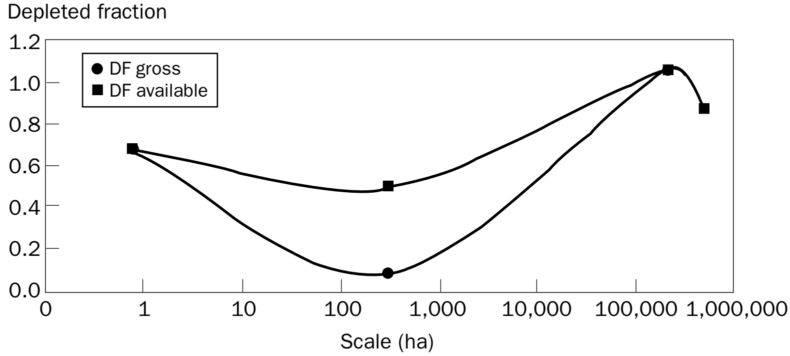

Fig. 4. Trends of depleted fraction (DF) per unit of gross inflow and available water over scale.

The water productivity per unit of gross inflow drops dramatically at the mezzo scale because of considerable (drainage) 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. Other factors apparently 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 is very high at the field scale where farmers are extremely cautious with the water they have to pay for. It decreases at the mezzo scale because of drainage out of the area and increases dramatically at the third main canal command scale because of reuse. Apparently, a certain size of 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.

The process fraction trend over scale (Fig. 3) shows that the process fraction per unit of gross inflow 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 mezzo scale, the value of the process fraction per gross inflow drops dramatically to 5%. This is explained by the huge amount of outflow, which is used again at the main canal command scale, where the process fraction of gross inflow increased again. At the subbasin scale, a slight decrease occurs, which is in line with a slightly lower rice land use at this scale.

The process fraction per unit of depleted water shows a downward trend going up the scales. Other land uses such as upland crops and noncropped areas gain more importance when the scale becomes larger.

The depleted fraction of gross inflow trend over scale (Fig. 4) again shows a downward trend from the field scale, where farmers are quite effective in capturing and storing rain, to the mezzo 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 outflow to more process depletion.

Discussion and conclusions

Results from the Tuanlin Irrigation Experiment Station and actual farmers' practices show that water-saving irrigation techniques such as alternate wet and dry irrigation reduce water deliveries to fields without significantly changing yield. Thus, water productivity per unit of water delivered to fields is higher with AWDI than with conventional practices.

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.

At the mezzo scale, the water productivity per unit of irrigation was consistently higher for Tuanlin (AWDI). In both cases, though, the values of water productivity per unit of irrigation were much lower than at the field scale. The process fraction of depleted water decreased to 0.55 in Tuanlin and to 0.42 in Wenjiaxiang and the depleted fraction of gross inflow decreased dramatically compared with the field scale. At the mezzo scale, other land uses such as upland crops and noncropped areas (trees, houses, roads, canals, ponds) play an important role. Following the nondepleted water (the outflow) downstream of the mezzo sites revealed that the outflow was captured and stored in a downstream reservoir that again supplied water to agriculture, cities, and industries downstream.

At the main canal command scale, the water productivity per unit of irrigation (measured by the Zhanghe reservoir releases) is three to almost six times as high as on the mezzo scale because of effective rainfall capture and use at this scale, thus lessening the need for Zhanghe water. As expected, the water productivity per unit of evapotranspiration remains almost the same. The process fraction of gross inflow increased, which means that more rainfall plus irrigation was converted to rice evapotranspiration than at the mezzo scale. However, the process fraction of depleted water decreased because other land uses besides rice increased beyond values obtained at the mezzo scale. Other land uses such as upland crops and noncropped areas gain even more importance at this scale. In the third main canal command, the depleted fraction of gross inflow increased markedly to a bit more than one. This indicates that either the water storage decreased (be it groundwater abstraction or soil moisture depletion) and was used for water consumption or measurement errors occurred in the inflow. Certainly most water is depleted within the area and not much outflow will be available for downstream use. The first and second main canal commands also have fairly high depleted fractions of gross inflow, but some outflow still occurs, which can be used downstream.

At the subbasin scale, the water productivity per unit of irrigation water is lower than the second and third main canal command and the weighted average value of the three main canal commands. Again, the water productivity per unit evapotranspiration remained about the same. The process fraction of gross inflow decreased slightly, which is in line with the small decrease in rice area at the subbasin scale. The process fraction of depleted water remained similar. The depleted fraction decreased to 0.88, meaning that only 12% of the inflow (irrigation and rainfall) is flowing out of the Zhanghe Irrigation District.

When we look at the trends over scale of the different water-accounting indicators, it becomes clear that the water productivity per unit of evapotranspiration remains more or less the same over all scales. It is obvious that the rice plant consumes the same amount of water for reproduction whatever the scale is. All other indicators show a decrease at the mezzo scale because of considerable (drainage) outflow from the domain. However, all indicators, except the process fraction per unit of depleted water, show an upward trend when going to the main canal command scale. This is explained by the reuse of water. Here it becomes clear that the ZID with its possibilities of capturing rainfall and runoff in all the reservoirs within the system is very effective in capturing and using water productively. Apparently, a certain size of scale is needed to have an effect from the reuse of water.

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 noncropped 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. Other land uses such as upland crops and noncropped areas gain more importance when the scale becomes larger.

Although the Yangtze basin is considered to be an open basin and inflow into the Yangtze can be considered as flow to a sink, since the water is not used downstream, the scope for developing new freshwater sources through water savings in the Zhanghe Irrigation District is limited. With only 12% of the rainfall and irrigation water releases flowing out of the basin, it is expected that the outflow cannot be further exploited without negative downstream effects on, for example, Chenghu Lake. The figures indicate that planners, designers, managers, and farmers have been quite effective in saving and using water in the ZID. This was accomplished by several strategies. Certainly at the farm scale, AWDI practices reduce the requirement for irrigation deliveries, thus allowing water to be stored in upstream reservoirs. Farmer practices also promote the capture and use of rain on their fields. The additional storage within the ZID clearly plays an important role in water savings. Drainage from fields, and more importantly runoff from nonrice land, is effectively captured for use within the system. Delivering limited volumes of water to farms and effectively managing reservoirs require sound canal operation and maintenance practices. Again, exemplary practices have been observed in the ZID and described in Loeve et al

(2001). Further improvements can be made in reducing costs of water delivery service and in improving the environment in the area.

In areas where water is severely limited, as in the third main canal command, there is no additional water to deplete, so the way to increase production is to increase the amount of kilograms per unit of crop evapotranspiration and reduce nonprocess evapotranspiration.

When focusing on increasing the water productivity per unit of irrigation, some caution is warranted. $WP_{irrigation}$ is highly dependent on rain. If a lot of rain occurs in one year, less irrigation water is required to achieve the same yield and the water productivity per unit of irrigation increases. Furthermore, in areas where there is considerable water reuse, as in the Zhanghe Irrigation District, a reduction in irrigation supplies at the field scale may or may not lead to an overall increase in productivity at the subbasin scale if the drainage water is reused downstream. However, if the field water savings could lead to a lower demand and the Zhanghe reservoir operators could keep the water stored high in the system, they could direct it to other more productive uses.

References

Allen RG, Pereira LS, Raes D, Smith M. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Rome (Italy): FAO. xxvi + 300 p.

Bastiaanssen WGM, Menenti M, Feddes RA, Holtslag AAM. 1998. A remote sensing surface energy balance algorithm for land (SEBAL). 1. Formulation. J. Hydrol. 212/213:198-212.

Bastiaanssen WGM, Ali S. n.d. A new crop yield forecasting model based on satellite measurements applied across the Indus Basin, Pakistan. J. Agric. Ecosyst. Environ. (In press.)

Chemin Y, Ahmad MD. 2000. Estimating evaporation from surface energy-balance model (SEBAL): a manual for NOAA AVHRR in Pakistan. IWMI-Pakistan Report No. 102. Lahore (Pakistan): IWMI-Pakistan.

Chemin Y, Alexandridis T. 2001. Improving spatial resolution of ET seasonal for irrigated rice in Zhanghe, China. Asian Conference of Remote Sensing 2001, National University of Singapore, Singapore. 8 p.

Chemin Y, Alexandridis T, Loeve R. 2002. Water productivity at different spatial scales from remote sensing, Zhanghe Irrigation District, Hubei Province, China. J. Irrig. Sci. (Submitted.)

Dong B, Loeve R, Li YH, Chen CD, Deng L, Molden D. 2001. Water productivity in Zhanghe Irrigation System: issues of scale. In: Barker R, Loeve R, Li YH, Tuong TP, editors. Water-saving irrigation for rice. Proceedings of an International Workshop held in Wuhan, China, 23-25 March 2001. Colombo (Sri Lanka): International Water Management Institute. p 97-115.

Li YH, Dong B, Yu F. 1999. Improving irrigation management of paddy fields for sustainable increases in water productivity. In: Musy A, Pereira LS, Fritsch M, editors. Emerging technologies for sustainable land use and water management. Proceedings of the 2nd Inter-Regional Conference on Environment-Water, 1-3 September 1999, Lausanne, Switzerland. Abstracts. Lausanne (Switzerland): Presses Polytechniques et Universitaires Romandes. Xv, 71 p. + CD.

Loeve R, Dong B, Zhao JH, Zhang SJ, Molden D. 2001. Operation of the Zhanghe Irrigation System. In: Barker R, Loeve R, Li YH, Tuong TP, editors. Water-saving irrigation for rice. Proceedings of an International Workshop held in Wuhan, China, 23-35 March 2001. Colombo (Sri Lanka): International Water Management Institute. p 25-53.

Mao Z. 1993. Principle and technique of water-saving irrigation for rice. China: Wuhan University of Hydraulic and Electrical Engineering. (In Chinese.)

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

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

Peng SZ, Yu SE, Zhang HS. 1997. Water saving irrigation techniques for paddy. Beijing (China): China Water and Hydro Publ. 155 p. (In Chinese.)

Tasumi M, Bastiaanssen WGM, Allen RG. 2000. Application of the SEBAL methodology for estimating consumptive use of water and stream flow depletion in the Bear River Basin of Idaho through remote sensing. Appendix C: a step-by-step guide to running SEBAL. Final Report. The Raytheon Systems Company, EOSDIS Project.

Tuong TP, Bhuiyan SI. 1999. Increasing water-use efficiency in rice production: farm-level perspectives. Agric. Water Manage. 40:117-122.

Wang GT. 1992. High-yield and water-saving irrigation method: deep-thin-alternate dry and wet. Irrig. Drainage Small Hydropower Sta. 8:18-19. (In Chinese, with an English abstract.)

Notes

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