Chapter 6

Water Productivity in the Zhanghe Irrigation System: Issues of Scale

B. Dong,[1] R. Loeve,[2] Y. H. Li[1], C. D. Chen,[3] L. Deng[1] and D. Molden[2]

Abstract

This paper explores factors behind the increase in water productivity at the Zhanghe Irrigation System (ZIS). To do so, we considered water use at different scales—farmers' fields, a mezzo scale and, finally, at the irrigation system or subbasin scale. By better understanding how farmer practices and other interventions "scale up," important insights can be gained that will contribute to improved design and management of irrigation for water-stressed environments. A water-accounting methodology developed by IWMI was applied to ZIS to evaluate the status of water use and productivity at different scales.

At the field scale, we looked at the on-farm water-saving irrigation (WSI) techniques, especially the AWD irrigation, that are widespread amongst farmers. It is hypothesized that AWD irrigation has been a major factor enabling the transfer of water to other higher-valued uses without significant loss in crop production. Our field studies verified that, by using AWD irrigation, farmers are very effective in converting water deliveries to crop evapotranspiration and limiting seepage and percolation. The results from the Experimental Station also show a significantly higher water productivity per unit of irrigation water under AWD irrigation techniques.

At the mezzo scale, other factors, including reuse of water, become important. Rainfall-runoff and the capturing of this runoff and return flows become dominant processes at this scale and the depleted and process fractions are lower while the water productivity per unit of irrigation water is reduced.

At the subbasin scale (considering irrigation and other uses), the long-term trend in water allocation across sectors and the trends in yield per hectare and per cubic meter of irrigation water supplied show there has been real water savings.

By performing the analysis at various scales, we demonstrate that there are several practices that ultimately influence water savings at the subbasin scale. These practices include on-farm AWD irrigation practices, a shift in the cropping pattern from two crops of rice to one crop of rice, volumetric charging, better delivery-system management, water reuse—

---

[1] Department of Irrigation and Drainage Engineering, Wuhan University, Wuhan, 430072, P. R. China.

[2] International Water Management Institute (IWMI), Colombo, Sri Lanka.

[3] Zhanghe Irrigation Administration Bureau, Jingmen, 448156, P. R. China.

primarily from the many small- and medium-sized reservoirs scattered throughout the area—and incentives for farmers and system operators to produce more rice with less water.

This paper demonstrates that perceptions of “water savings” are scale-dependent and are related to the objectives of water managers operating at that scale. There are several definitions of water productivity, each with special implications, so it is important to clearly define the term used in research, presentations and discussions.

Introduction

Rice and Water

Growing more rice with less water is one of the major challenges of the twenty-first 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. Where will this water come from? It is becoming increasingly difficult to develop new freshwater sources not only because difficulties are encountered with the development work of new, large infrastructure but also, in many cases, because the physical limit to the amount of water that can be developed is being reached. Much of the water will have to come from water savings—and rice, a water-intensive crop, is a major target for such savings.

We will first present some basic concepts of water savings and issues of scale, then show how practices at the farm level are upscaled in the ZIS, Hubei Province, P.R. China.

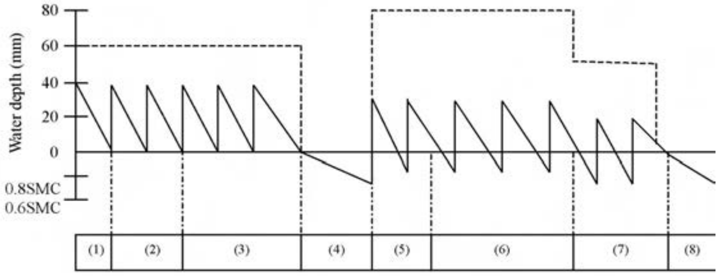
Water Savings

Major efforts have already been made to save water in rice irrigated areas and there is much to learn from previous efforts, particularly in China where research and practice are well advanced. Many practices have been developed for farmers to deliver less water to their fields and these are collectively known as WSI practices (Wang 1992; Mao 1993; Peng et al. 1997), for example, AWD irrigation (see figure 1), which has spread in south China (Li et al.1999). This practice is being implemented on a large scale as in the ZIS. A question of global interest is whether this practice has led to “real” water savings, which can be transferred to other agricultural and nonagricultural uses. One of the difficulties in answering this question is that it is difficult to know if and how farm-level practices scale up to basin-level savings.

One difficulty in communicating about “water savings” is that this term carries different meanings to different people. The meaning is often dependent on the scales of interest. Farmers would typically like to make some more money from their resources. If they have to pay for water, by paying either energy costs of providing water or costs of a service provider, there may be sufficient incentive to apply less water. Another example is that when a limited supply of water is rationed farmers have an incentive to keep their production levels high with this limited amount of water. In these farm-level cases, the term “water savings” most often refers to a reduction in irrigation water applied to crops (Tuong and Bhuiyan 1999).

Interests of society come into play at the basin scale. In many basins of the world, there are growing demands for water of good quality for nonagricultural uses—the environment,

Figure 1. Graphical description of the AWD irrigation regime.



(1) Transplanting, (2) Revival of green, (3) Early and middle stages of tillering,
(4) Late state of tillering, (5) Elongating and booting, (6) Heading and flowering,
(7) Milk ripening, (8) Yellow ripening (SMC = Saturated Moisture Content).

cities and industries. Also, there remains a need to grow more food and support farmers' livelihoods. In these situations, irrigated rice agriculture is a relatively low-valued use of water; so, there is pressure to meet other demands first and then let agriculture have the remaining water. At the basin scale, a common interest is in reducing the total amount of water depleted by irrigated agriculture whilst maintaining or increasing production. At this scale, we consider the total amount of basin resources and how they are allocated across sectors and uses and across the basin, temporally and spatially. If less water is depleted by agriculture, more will be available for other uses.

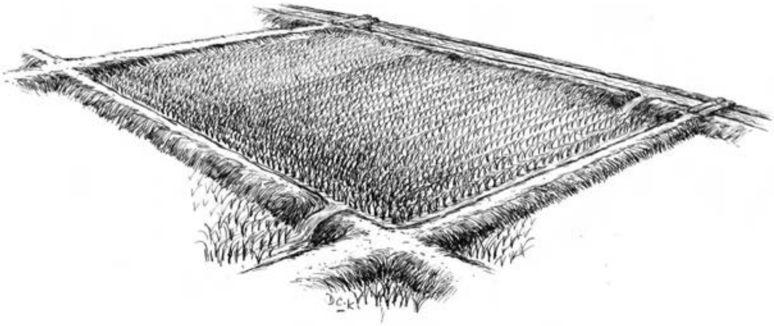
Water-saving practices at the farm scale, with the objective of reducing supplies to farms, do not necessarily lead to transferable savings at the basin scale—where the objective is for rice irrigation to deplete less of the basin water resource. Water savings, as we will demonstrate, constitute a phenomenon that is related to scale. The scale effect can be large because recycling of water is prevalent in basin water-resource systems, especially where rice is a major crop. In addition, as the scale of interest grows from 1 hectare to 100 hectares and up to more than 10,000 hectares, other uses of water start to interact more with water use for rice when the scale of interest grows. These concepts are illustrated using the ZIS.

Issues of Scale in Rice Areas

To illustrate issues of scale, we will use different scale-related illustrations of rice growing at ZIS. At the farm scale, farmers receive water from various sources: rain, the irrigation canal, ponds, drains or groundwater. Various field-scale practices and processes play a critical role in field-scale water use: frequency, timing and volume of application, field preparation to control percolation and seepage and to capture rain, fertilizer use, pest control and more. Figure 2 illustrates the situation from the point of view of an observer standing next to the field.

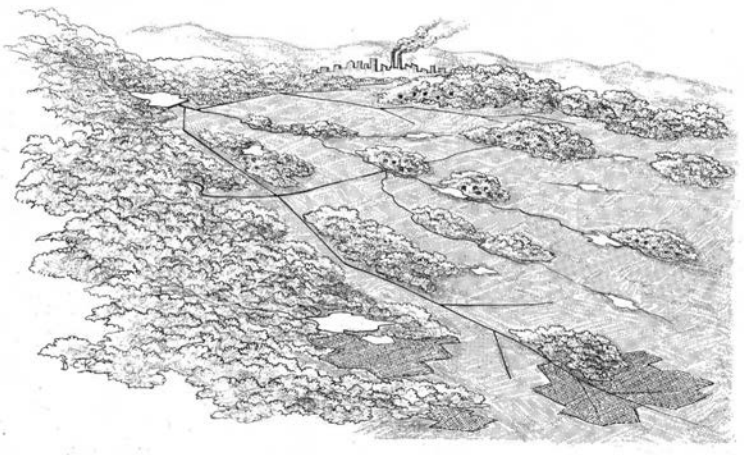
For the research we selected six fields in two sites, one site to represent situations where AWD irrigation is said to be widely practiced and another site where AWD irrigation is said not to be so common. One site was selected near the Tuanlin Irrigation Experimental Station (with AWD irrigation), about 20 km southeast of the Zhanghe reservoir and another in WJX township (without AWD irrigation), about 35 km northeast of the Zhanghe reservoir.

Figure 2. A field-scale point of view.



If we could take a balloon ride we would have a different point of view as illustrated in figure 3. Here we look at an area of about 300 hectares. The landscape 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; and practices and processes related to nonirrigation uses of water. Irrigation water enters a rice field, is drained into a small pond, and then is used again for rice, after which it flows out of the area. Rainwater falls on nonirrigated areas, is also trapped in a pond, is diverted to a rice field and then enters the main drain. Even within this mezzo scale, there is ample opportunity for reuse. But there are also drainage flows out of the area.

Figure 3. The view at a mezzo scale. The flow paths of water are from field to field, to drain, to reservoir and then back to the field. Other nonagricultural uses influence overall water use.

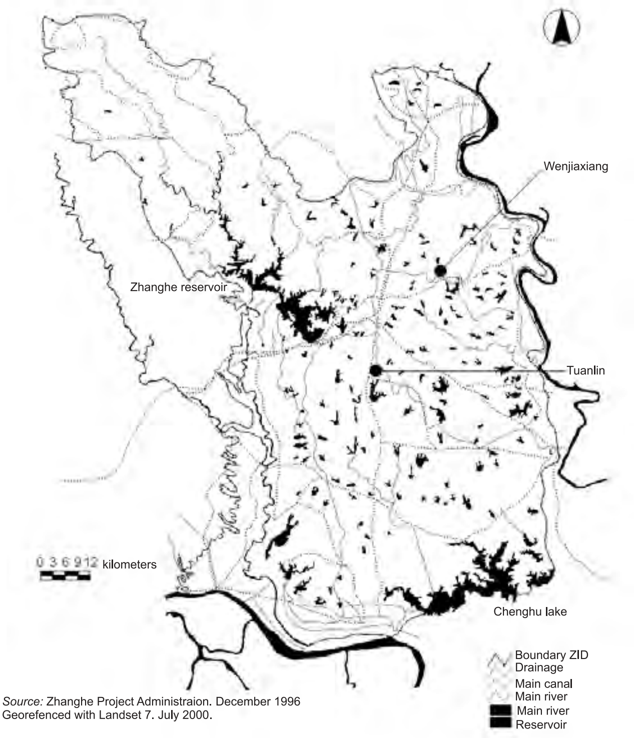


For this research, the two sites representing this scale are the TL and WJX pilot areas. The TL pilot area is irrigated by the first branch of the third main canal and a small-sized reservoir upstream. The total area is 287 hectares of which about 41 percent are rice fields. The WJX pilot area is supplied by the east branch of the fourth main canal and is located at the tail end of the canal. The total area is 606 hectares of which about 28 percent are rice fields. The northern part of the area is hilly and the elevation decreases gradually from north to south. The main crop in 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 unirrigated.

Going up a little higher in the balloon we get yet another picture. A major feature of the landscape is a medium-size 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.

If we could take an airplane ride, we would see the whole of ZIS. We would find that it is dotted with thousands of reservoirs of various sizes (figure 4). We would also see the delivery infrastructure. We notice that at the tail there is a major lake that captures drainage flows from the ZIS.

Figure 4. The view of the area served by the ZID.



Source: Zhanghe Project Administraion. December 1996
Georefenced with Landset 7. July 2000.

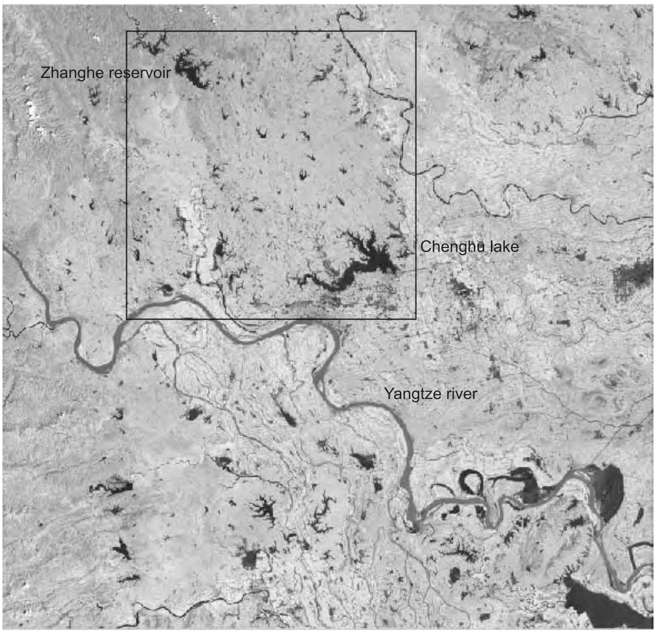
Note: While the landscape is dominated by agriculture other nonagricultural uses of water are also very important. Water bodies are a prominent feature in the landscape.

For the research we considered the entire Zhanghe Irrigation District (ZID) as the subbasin scale. The ZIS is one of the typical large-sized irrigation systems in China with a total area of 5,540 km^2 of which about 160,000 hectares constitute the 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 a large number of branch canals with a total length of more than 7,000 km. A large irrigation network, including large-, medium- and small-sized reservoirs for purposes of storing, diverting and withdrawing water, has been established. The main crops are rice, winter wheat, sesame and soybean with rice fields occupying about 80 percent of the total irrigated area.

Since the 1980s, a rehabilitation and improvement program has been carried out to improve the performance of the ZIS. In addition to infrastructure, the program has included popularization of AWD irrigation, canal lining, volumetric charging, drainage water reuse and other management innovations.

Finally, a satellite image (figure 5) shows the ZID fitting into the Yangtze river basin. We see the ZID bounded by the Han river on the northeast and the Yangtze river on the southwest, with the Yangtze river dominating the scene. Many water bodies fill the landscape in this water-rich environment. Water-management processes and practices include flood control and allocation between sectors. In spite of having a wealth of water, there is still a problem of meeting demands and problems of flooding because of the temporal variations in rain. In Zhanghe, water released by hydropower flows down the Yangtze river. In spite of apparent abundance, saving water and reallocating it are extremely important to meet other needs.

Figure 5. Landsat 7 image of the Zhanghe area. The ZID is located within the box.



Research Objectives

Scientists from the International Water Management Institute (IWMI) and the International Rice Research Institute (IRRI) are collaborating with Chinese scientists and water managers to find ways to produce “more rice with less water.” They are addressing some of the technical and institutional issues underlying the successful application of AWD irrigation techniques—for example fertilizer use, financial costs and benefits to farmers, implications of the eventual large-scale adoption of these techniques on water savings and increases in water productivity. This is particularly important for China where per capita freshwater availability is among the lowest in Asia and is still declining.

The objectives of this paper are to: a) Quantify the water productivity at different scales ranging from the field scale to the subbasin scale. b) Quantify the water productivity under AWD irrigation and non-AWD irrigation practices and get a better understanding of the “scaling up” of water-saving practices, which helps to gain important insights on the design and management of irrigation that will lead to transferable water savings. c) Explore factors behind the increase in water productivity at the ZIS. Through this research, we are testing the commonly heard assumption that the popularization of AWD irrigation has enabled water managers to transfer water away from agriculture to other higher-valued uses without any significant loss in crop production.

Methods and Materials

Methodology

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. Water accounting indicators are presented in the form of fractions and in terms of productivity of water. The water accounting system was considered at different spatial scales: a micro scale at the size of a field or a set of fields, a mezzo scale covering 300 to 600 hectares, and a subbasin scale covering the entire ZIS area. The scales were chosen to capture the scale effects of farm-scale interventions.

Two sites were selected to represent situations where AWD irrigation is said to be widely practiced (TL); and another site where AWD irrigation is said not to be so common (WJX). Within both sites, data were collected at the micro scale and at the mezzo scale.

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).

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.

Evapotranspiration. The reference evapotranspiration (ET_0) was calculated with the Penman-Monteith equation. All meteorological data for the ET_0 calculation are from the Tuanlin Irrigation Experimental Station. The meteorological data are manually observed thrice a day (at 08:00, 14:00 and 20:00). Monthly averages were used as input for the ET_0 calculations. The actual evapotranspiration was calculated by multiplying the ET_0 with a crop coefficient. The evaporation from open water (ponds, canals) was calculated with pan-evaporation data from the Tuanlin Irrigation Experimental Station.

Rainfall. Rainfall measurements were taken daily both in TL and WJX.

Surface water inflow and outflow. Inflow and outflow of surface water were measured at the boundaries of the study area (both at the micro and at the mezzo scale) twice a day. The discharge was measured using different measurement structures, like 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 with 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., 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 subbasin scale, secondary data were collected on water releases from the Zhanghe reservoir.

Storage change was calculated only in 2000 for a) *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; b) *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 c) *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 with the specific yield of the soil (estimated specific yield 0.10).

Water levels in fields. The water levels in the selected fields 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 subbasin scale, secondary data were collected on crop production.

Water Accounting Indicators

Water productivity (WP). The water productivity per unit of irrigation water ($WP_{irrigation}$) is the rice production divided by the irrigation inflow. The water productivity per unit of gross inflow (WP_{gross}) is the rice production divided by the rain plus irrigation inflow. The water productivity per unit of evapotranspiration (WP_{ET}) is the rice production divided by the rice evapotranspiration.

Depleted fraction (DF). The depleted fraction of gross inflow (DF_{gross}) is the evapotranspiration by all uses divided by rain plus irrigation inflow.

Process fraction (PF). The process fraction of gross inflow (PF_{gross}) is the rice evapotranspiration divided by rain plus irrigation inflow and indicates the amount of gross inflow that is depleted by ET_{rice}. The process fraction of depleted water (at the mezzo scale) is the rice evapotranspiration divided by evapotranspiration from all uses.

Results

Micro Scale

Experimental station. Table 1 shows the long-term rice yields under experimental conditions at TL for 10 years under traditional irrigation practices and AWD irrigation. The variation of yield over the years is high for both traditional irrigation and AWD irrigation. The yield difference between the two methods is not statistically significant. However, when we look at the water productivity per unit of irrigation water it shows that under AWD irrigation the water productivity is much higher (average 27%) than under the traditional practice.

Table 1. On-farm water productivity and depleted fraction under traditional and AWD irrigation practices.

	Rice yield (kg ha^{-1})		WP irrigation (kg m^{-3})		WP_{ET} (kg m^{-3})		WP gross (kg m^{-3})		PF_{gross}	
	Traditional	AWD	Traditional	AWD	Traditional	AWD	Traditional	AWD	Traditional	AWD
1991	6,701	7,751	1.62	1.92	1.54	1.56	0.88	1.03	0.57	0.66
1992	10,200	10,050	2.38	2.45	2.11	1.95	1.13	1.13	0.53	0.58
1993	8,378	10,497	1.59	2.15	1.39	1.66	0.86	1.12	0.62	0.67
1994	7,277	9,756	1.37	1.91	1.22	1.66	0.71	0.97	0.58	0.58
1995	7,689	9,873	1.20	1.59	1.04	1.40	0.77	1.02	0.74	0.73
1996	10,808	10,235	4.28	4.84	2.14	2.20	1.23	1.22	0.57	0.55
1997	9,969	9,455	1.56	1.78	1.41	1.35	0.75	0.77	0.53	0.58
1998	8,561	8,658	2.19	3.33	1.41	1.49	0.85	0.98	0.60	0.66
1999	8,332	8,015	1.81	2.94	1.39	1.34	0.99	1.23	0.71	0.92
2000	7,726	7,496	1.45	1.77	1.24	1.20	0.82	0.85	0.66	0.70
Average	8,564	9,179	1.95	2.47	1.49	1.58	0.90	1.03	0.61	0.66
sd.	1,349	1,106	0.90	1.00	0.36	0.30	0.17	0.15	0.07	0.11
p-value (T-test, paired)	0.147		0.001		0.177		0.005		0.033	

Source: Tuanlin Irrigation Experimental Station.

At the micro scale, a lot of water is saved under AWD irrigation. The water productivity per unit of evapotranspiration was similar for each treatment and not significantly different. The rice plant still needs the same amount of water, and all the water savings come from less evaporation and percolation. According to data from the TL station, percolation and drainage under AWD irrigation were, respectively, 10 percent and 21 percent less than that under traditional irrigation practices.

The process fraction of gross inflow {PF_{gross} = ET/(rain plus irrigation)} indicates the amount of gross inflow that is depleted by rice ET. At the field scale, PF_{gross} is significantly higher under AWD irrigation. However in both cases, values of PF_{gross} over 60 percent represent fairly precise rice irrigation practices. These are results from the experimental station—what do farmers actually practice?

Micro scale—farmers' fields. The summary of water accounting at the micro scale within the two mezzo sites in 1999 and 2000 is shown in table 2. All components of the water balance were measured except for the evapotranspiration. The results in table 2 show that

*Table 2. Water accounting at the micro scale in TL and WJX.**

	Year 1999		Year 2000	
	TL	WJX	TL	WJX
Gross area (m^2)**	7,607	7,788	7,606	7,788
Net area (m^2)	7,445	7,577	7,445	7,577
Inflow (mm)				
Irrigation	274	438	424	533
Rainfall	377	379	463	410
Gross inflow	651	817	887	943
Storage change (mm)			+18	+6
Net inflow	651	817	869	937
Depletion (mm)				
ET (rice)	603	603	623	623
Total depleted	603	603	623	623
Total outflow (mm)***	253	144	212	155
Performance				
Process fraction of gross inflow (ET/irrigation+rain)	0.93	0.74	0.71	0.66
Unhusked rice yield (kg/ha)	7,890	8,610	7,430	7,770
Production per unit (kg/m^3)				
Irrigation water	2.90	1.98	1.81	1.48
ET	1.31	1.43	1.19	1.25

* Average value of three fields; ** Gross area is the net area plus the area occupied by bunds; *** The total outflow includes drainage and deep percolation.

the water balance is not closed. In the 2 years, rice yields in WJX (non-AWD irrigation) were a little higher than those in TL (AWD irrigation), but irrigation water use was much higher compared to TL, leading to higher average values of $WP_{irrigation}$ for TL. Values for WP_{ET} were similar between sites for both years.

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 in 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. The year 2000 was unusual in the sense that there was a drought in the early season resulting in farmers applying more water. At the end of the season, there were heavy rains resulting in higher rainfall values for 2000 compared to 1999.

All water productivity values per unit of irrigation water ($WP_{irrigation}$) are higher under AWD irrigation than under the traditional irrigation method. This cannot be explained only by the higher yield for AWD irrigation. As an average over the 2 years, the yields are only 7 percent higher while the $WP_{irrigation}$ values are up to 34 percent higher. This is because of lower irrigation water input for AWD irrigation.

Although none of the fields we monitored practiced a pure form of AWD irrigation (as described in figure 1) or traditional irrigation practice, the field water-level measurements show that in TL a form of irrigation much closer to AWD irrigation was practiced than in WJX. Besides that, in TL the number of days without standing water on the fields was much larger than in WJX. Data from the Tuanlin Experimental Station show that percolation and drainage under AWD irrigation were, respectively, 10 percent and 21 percent less than that under traditional irrigation practices. The slight difference between the two irrigation methods and water productivity values per unit of evapotranspiration (WP_{ET}) of about 8 percent imply that the higher rice yield is in line with the higher rice evapotranspiration.

Mezzo Scale

The water accounting components and indicators for the two mezzo-scale sites in 1999 and 2000 are summarized in table 3.

In line with the field observations for the two irrigation seasons, more water was diverted to the two sites in 2000 than in 1999. This is because of a serious water shortage from May to July in 2000, which resulted in a longer duration of canal operation, and more irrigation applications. However, in 1999 and 2000, the irrigation duty in TL was 29 percent and 21 percent less, respectively, than in WJX. Yields at both sites were reduced in 2000 possibly due to water stress and pests.

For the two mezzo sites, the depleted fraction of gross inflow ranges from 0.09 to 0.20 (meaning 9% to 20% of the rain plus irrigation are depleted by evapotranspiration by all uses) and is much lower than at the field scale. The ratio of rice field to total area for the two sites is about 41 percent at TL and 28 percent at WJX. In TL and WJX, rice consumes 55 percent and 42 percent, respectively, of the depleted water. Obviously at the mezzo scale, other land uses such as upland crops and non-cropped areas (trees, houses, roads, canals, ponds) play an important role.

Table 3. Water accounting at the mezzo scale in TL and WJX.

	Year 1999		Year 2000	
	TL	WJX	TL	WJX
Total area (ha)	287	606	287	606
Rice field area (ha)	117	179	117	167
Inflow (mm)				
Irrigation (total area [ha])	2,938	1,358	4,543	1,696
Other surface inflow	33	56	94	22
Rainfall	385	385	463	408
Gross inflow	3,356	1,799	5,100	2,126
Storage change (mm)	-	-	-5	-181
Outflow (mm)				
Committed outflow	2,631	1,045	4,055	1,277
Utilizable outflow	415	116	525	103
Total outflow	3,046	1,161	4,580	1,380
Irrigation duty (for rice) (mm)	755	1065	1199	1523
Unhusked rice yield (household survey) (kg/ha)	7,430	8,440	6,330	6,440
Indicators				
Depleted fraction of gross inflow	0.13	0.20	0.09	0.20
Process (rice) fraction				
of gross inflow	0.09	0.08	0.05	0.08
of depleted water	0.56	0.41	0.54	0.42
Production per unit (kg/m^3)				
Irrigation water	0.98	0.79	0.53	0.42
ET	1.04	1.72	1.00	1.01

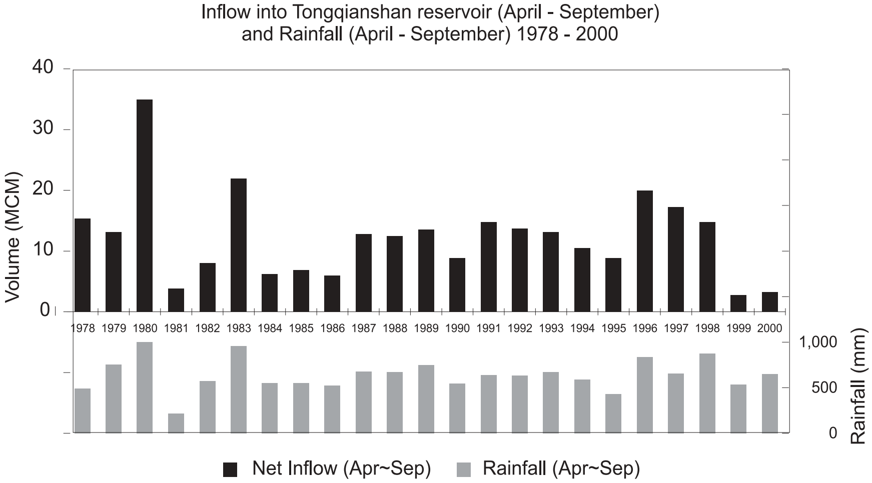
Note: Yield data were obtained from a socioeconomic survey with a sample size of 30 except for TL in 1999 where the sample size was 22 households (2 outliers were eliminated).

What happens to the non-depleted water—the outflow? A field investigation at both sites revealed that the outflow was captured and stored in a downstream reservoir that again supplied water to agriculture, cities and industries downstream.

Some investigations on these reservoirs downstream of the mezzo sites revealed some interesting information. In both cases, the reservoirs were at one time part of the ZIS, but are now operated independently of the ZIS. Both are connected to the ZIS reservoir with a canal but reservoir operators rarely take water from the ZIS because of the additional cost in purchasing the water. The water source for the reservoir is the runoff from non-rice lands plus the drainage from rice fields. We thought that if drainage from rice fields decreased over time, so must the inflow into the reservoir. But the results revealed an opposite trend (figure 6) warranting further investigation

Compared to the indicator at the field scale, $WP_{irrigation}$ values at the mezzo scale are lower. The reason for this is that much of the irrigation supply into the mezzo area does not get applied to rice fields probably due to canal seepage and operational spills. Thus at the mezzo scale, other non-rice factors are significant and the depleted and process fractions are lower and the $WP_{irrigation}$ is reduced. Will these continue to decrease as the scale of interest increases?

Figure 6. Inflow into the Tongqianshan reservoir 1978–2000.



System and Subbasin Scale

Similar data on the water balance are not yet available for the entire subbasin (including the irrigation system, nonirrigated crops, cities and industries). Nevertheless, from existing secondary data, it is possible to obtain an indication of scale effects regarding the productivity of water. Figure 7 shows the long-term data on irrigation water from the Zhanghe reservoir, rice-irrigated area and rice production in ZID. The share of water supplied to irrigation was dominant until the 1980s. Afterwards, the Zhanghe reservoir water was used to meet the growing demand for water for industry, municipal and hydropower use, and the amount of water from the reservoir allocated to irrigation has declined. From 1966 to 1978, the annual average amount of water diverted to irrigation from the reservoir was 603 mcm; from 1979 to 1988, it was 362 mcm, while from 1989 to 1998 it was reduced to 212 mcm (Hong et al. 2000).

With the reduced allocation of water for irrigation, the rice area directly irrigated by the reservoir declined over the years. During the 1990s, the area was reduced by about 28 percent from the level in the 1980s (see figure 7). Despite the decline in the Zhanghe reservoir releases for irrigation, rice production continued to rise until the 1990s, where there has been about a 10-percent reduction in the past 10 years (see figure 7) due to the decrease in rice areas. The major factors that contributed to the sustained growth in rice production included the spread of hybrid rice varieties and increased use of chemical fertilizer.

Over time, rice production per cubic meter of irrigation water ($WP_{irrigation}$) released from the Zhanghe reservoir has shown an upward trend as shown in figure 8. The annual average $WP_{irrigation}$ during the period 1966–78 was 0.87 kgm^{-3}, then rose to 1.44 kgm^{-3} in the second period, 1979–88. The value for the last period, 1989–98 2.61 kgm^{-3}, shows it has tripled from that for the first period.[4] Note that we do not yet have information to calculate comparable WP per unit of water depleted, and various process and depleted fractions at this scale.

---

[4] The supply of water into the Zhanghe irrigated area is from rain, plus supplies from the Zhanghe reservoir. There are internal supplies in the command area, but these essentially capture rain, or Zhanghe reservoir water. Thus we calculated water productivity of the Zhanghe reservoir water only, and not of all the sources of water within the irrigated area.

Figure 7. Annual planted rice area directly irrigated by Zhanghe reservoir (1,000 ha), rice production (1,000 tons) and irrigation water (mcm) from the Zhanghe reservoir (1966–1998).

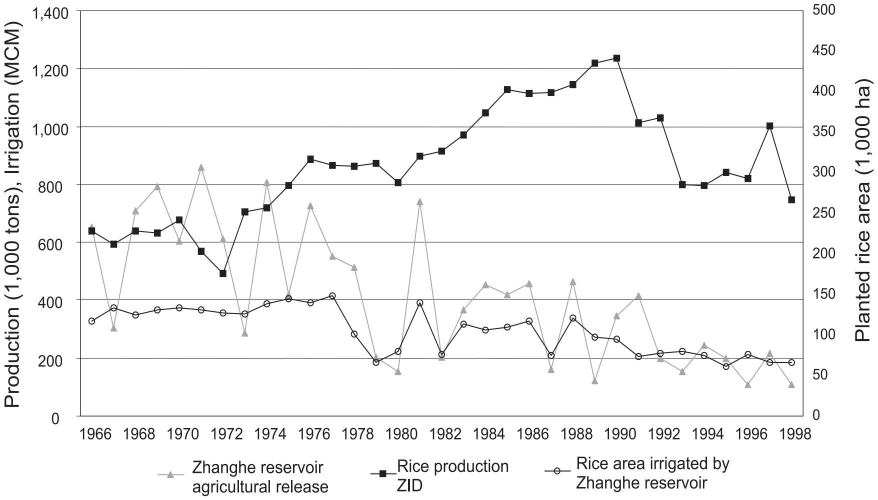
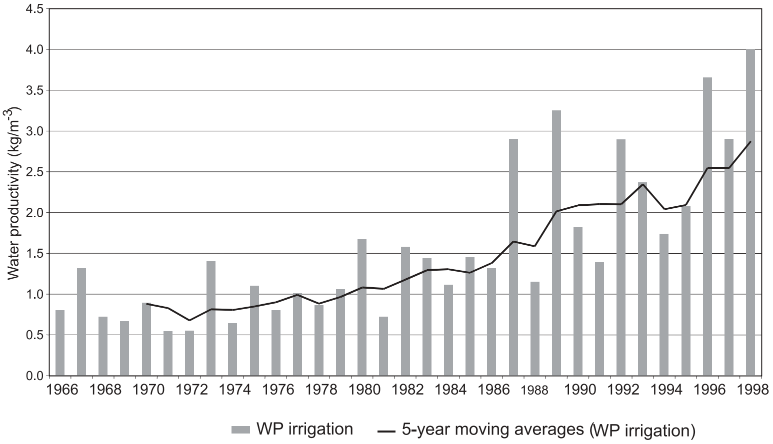


Figure 8. Trend of WP$_{irrigation}$ (1966–1998).



Water Savings and Productivity of Water

Water Savings and Water Flow Paths

This paper has demonstrated that perceptions of "water savings" are scale-dependent and are related to the objectives of water managers operating at that scale. At the farm scale, "water savings" are related to reducing applications of irrigation water. At the basin scale, water savings in one area are practiced to transfer water to a different area or a different water-use sector.

It is probably more constructive to think about flow paths of water, rather than water savings to understand how to increase the productivity of water. Although we have not quantified it, it could be argued that the amount of water entering the Yangtze river has not been heavily influenced by water-management practices at ZIS. The construction of the Zhanghe reservoir changed the timing and the flow path of water to the river. In the initial years of operation, the major flow path of water was through the agricultural land, then draining back into the Yangtze system. After the 1980s, with the introduction of hydropower and more urban uses, flows were redirected to hydropower uses and to cities and then back to the Yangtze river.

Within the irrigated area, the flow paths of water have been altered over time. At the micro scale, the flows are from field to field to drains. When there were fewer downstream reservoirs, the opportunity for reuse was less, and drainage water directed water out of the irrigated area. With more reservoirs, downstream flows were recaptured and reused. Pumps also provided a technology to intensify reuse. Simultaneously, though deliveries to farms from the Zhanghe reservoir were reduced, encouraging farmers to seek other sources, the Zhanghe reservoir operators could keep the water stored high in the system and direct it to other more productive uses.

Productivity of Water

With increasing water scarcity, productivity of water is emerging as a very important concept. The productivity of water can be defined as the mass of production per unit of water. It has been more broadly used to refer to the additional value produced per unit of water (see text box 1 for details about Zhanghe). Almost immediately, we have problems in defining the water term—productivity of which water? More crop per what drop? There are a few ways to think about productivity of water, all of which are valid, but each having a different significance. The main message is to be clear about how the term "water" is defined.

Text box 1. Details about Zhanghe.

> The productivity of water for ZIS must have increased tremendously over the last 40 years. Initially, after reservoir construction most of the water was used for low-yielding rice. Now the same water is used for high-yielding rice, plus high-valued uses in cities, industries, hydropower and fisheries. There are also costs and benefits of environmental uses that could be quantified to get an indication of the overall changes in the productivity of water.

An important definition of the productivity of water in agriculture is certainly the amount of mass produced per unit of water depleted by evapotranspiration (WP_{ET}). Note that both irrigation water supplies and rain contribute to crop evapotranspiration. Getting more kilograms per unit of evapotranspiration is particularly important in areas where water is severely limited, such as in the Yellow river. There is no additional water to deplete, so the way to increase production is to obtain more kilograms per unit of evapotranspiration.

Another measure of productivity of water focuses on the irrigation supply ($WP_{irrigation}$). At the field scale, practices such as AWD irrigation reduce water application. Even without an increase in yield, productivity of irrigation supplies at the field scale increases. Some caution is warranted when considering this term ($WP_{irrigation}$) for a few reasons. First, the term is highly dependent on rain. If there is a lot of rain in one year, less irrigation water is required to achieve the same yield and the productivity of irrigation supplies may go up! Second, in areas where there is considerable reuse, productivity of supplies at the field scale may or may not lead to an overall increases in production at the system scale if the drainage water is reused in other fields.

Moving up the scale to the irrigation system, further considerations are warranted. The mass of production per unit of water depleted by the irrigation system is a fundamental concern, especially in water-stressed basins. Here water is depleted by crop evapotranspiration, evapotranspiration of other plants, evaporation from open water surfaces, and by drainage flows directed to sinks like saline aquifers, or water in excess of environmental requirements draining to seas.[5] Means of obtaining more productivity per unit of water depleted are to reduce evaporation, non-beneficial evapotranspiration and flows to sinks, and increase the amount of kilograms per unit of crop evapotranspiration.

For reservoir managers, productivity per unit of supply also carries an important meaning. Society has paid costs to develop this supply, so there is also a societal interest in the productivity of water. How can more benefit be squeezed out of every drop of investment (see text box 2 for details about Zhanghe)? Again, productivity of water per unit of supply must be treated with caution. One could have also added up all the water supplied by the thousands of reservoirs within the Zhanghe area, and compared production against the sum of all supplies. In this case, the productivity per the sum of all supplies would not have risen as sharply. The approach to increase the productivity of reservoir supply was arguably to make more use of the rain falling on the Zhanghe area by capturing it in these smaller reservoirs, allowing for other uses of the Zhanghe reservoir water.

Text box 2. Details about Zhanghe.

This return on investment is what was tracked over time in figure 8; the agricultural productivity of the Zhanghe reservoir supply showed a dramatic increase. The change in value added per unit of reservoir supply would likely show a more remarkable increase with deliveries shifted away from agriculture to cities.

Molden and Sakthivadivel (1998) define available water as the water supply plus rain into a domain of interest less water committed to downstream uses. This represents the amount of water available for depletion within an area. We argue that this is a consistent and fundamental approach to consider the productivity of water within a domain of interest. At the Zhanghe, water managers have deployed means of capturing rainfall to better utilize their available supply, and the productivity of water per available supply has increased.

---

[5] Drainage flows to the Yangtze could be considered as flows to sinks because there are no users of this water downstream.

Basin Implications of Water Savings and Water Productivity

Last, but not least, basin considerations temper how various definitions of productivity of water are interpreted. In the Yangtze basin, there is apparently scope for depleting additional supplies without reducing the quantity of water available for downstream users (recognizing that quality may deteriorate). In contrast, on the Yellow river, upstream development and additional depletion impact downstream users. We say the Yangtze basin is open while the Yellow river is closed for new development or additional depletion. This important distinction makes a huge difference in how productivity of water is viewed.

In an open basin, like the Yangtze, we can increase productivity of water supplies by depleting more water in a beneficial manner such as through additional crop evapotranspiration or through urban or industrial uses. Whether or not more water is evaporated is not a huge concern. In a closed basin, like the Yellow river, productivity per unit of water depleted (taking care not to deplete more than is available), or productivity of available water is a more important indicator to track. Means of increasing the productivity of available water are to reduce depletion that is not of high benefit, or increase the benefits derived from depleting a unit of water. It is possible to increase the productivity per unit of supply at the irrigation-system scale, but decrease the overall benefits taken from a basin perspective. Decreasing supplies, as was helpful in the Zhanghe area, may or may not lead to increases in the productivity of available water.

Conclusions

This paper explores issues of scale in WSI practices. At ZIS, AWD irrigation practices are common at the field scale. Do these contribute to water savings and increases in productivity of water for the irrigation system? If so, how?

The water accounting result at the micro scale shows that the farmers are effectively able to capture rainfall and irrigation water supplied to fields and convert this into productive crop evapotranspiration. The amount of gross inflow (rain + irrigation) that is depleted by rice evapotranspiration fraction of gross inflow at the field scale is commonly more than 65 percent. The production per unit of irrigation water was typically higher for TL where farmers practice AWD irrigation.

At the mezzo scale, other non-rice uses gain importance. A much smaller proportion (less than 10%) of the gross inflow is converted into rice evapotranspiration. The production per unit of irrigation water decreased at the mezzo scale than at the field scale. This is explained by the considerable runoff from non-riceland at the two mezzo sites. However, a considerable amount of the outflow is not wasted but captured and stored in downstream reservoirs that again supply water to agriculture, cities and industries downstream. Runoff capture and irrigation reuse become important for water savings as scales become larger.

The subbasin scale shows an increase in water productivity compared to the mezzo scale. Here it becomes clear that ZIS, with its possibilities of capturing rainfall and runoff in all the reservoirs within the system, is very effective in capturing and using water for productive use. Water capture and reuse are of major importance at this scale of analysis. We do not yet have enough information to calculate indicators at the subbasin scale to compare them with those at the mezzo and micro scales.

The subbasin-scale analysis indicates that there is an increase in the water productivity over time and that real water saving takes place. Water productivity of irrigation supplies approaches the values found at the field scale. There are a number of factors that may have contributed to water saving and increasing the productivity of water over time. The increase in water productivity has been due to several factors including AWD irrigation, a shift in the cropping pattern from two crops of rice to one, volumetric charging, better management of the delivery system and water reuse, primarily from the many small- and medium-sized reservoirs scattered throughout the area. On-farm AWD irrigation practices and effective use of rainfall have contributed as a demand-reduction measure. Water managers and farmers have effectively constructed and employed thousands of micro- to medium-size reservoirs to capture and store water within the command area and allow a substantial amount of reuse. Runoff generated inside the irrigation system from non-rice lands and drainage from rice fields is captured and used again replacing the need to release the Zhanghe reservoir water. Reservoir water managers can thus keep the water in the reservoir and use it to meet other uses. In fact, if productivity of water were measured in terms of rice production plus additional benefits from hydropower, industry and cities, marked increases over time would be demonstrated.

The research has led to several questions about the concepts of water savings and water productivity. These are very important concepts, especially in situations of scarcity and competition. There are several definitions of water productivity, each with special implications, so it is important to clearly define the term used in research, presentations and discussions. It is argued that in closed basins such as the Yellow river, productivity per unit of water depleted has more relevance than productivity per unit of supplies, which has relevance in open basins like the Yangtze.

Because water savings in rice areas constitute such an important task it is important to gain further understanding of the strategies to be employed to save water, to increase the productivity of water under a variety of physical and institutional environments. This study shows that there is much to be learned from existing practices and demonstrates that a combination of factors can be important in achieving real water savings.

Literature Cited

Hong, L.; Y. H. Li; L. Deng; C. D. Chen; D. Dawe; R. Loeve; and R. Barker. 2000. Impact of water-saving irrigation techniques in China: Analysis of changes in water allocations and crop production in the Zhanghe Irrigation System and District, 1966 to 1988.

International Water Management Institute. 2001. *Annual report 1999-2000.* Colombo, Sri Lanka

Li, Y. H.; B. Dong; and F. Yu. 1999. Improving irrigation management of paddy fields for sustainable increases in water productivity, In *Emerging technologies for sustainable land use and water management*, ed. Andre Musy, Luis Santos Pereira and Martin Fritsch. Lausanne, Switzerland.

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

Mao, Z. (Forthcoming). Water-saving irrigation regimes of rice in China.

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

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

Peng, S. Z.; S. E. Yu; and H.S. Zhang. 1997. *Water saving irrigation techniques for paddy.* Beijing, China: China Water and Hydro Publ., 155pp (in Chinese).

Tuong, T. P.; and S. I. Bhuiyan. 1999. Increasing water-use efficiency in rice production: Farm-level perspectives. *Agricultural Water Management* 40: 117–122.

Wang, G. T. 1992. High-yield and water-saving irrigation method: Deep-thin-alternate dry and wet. *Irrigation and Drainage and Small Hydropower Station 8*: 18–19 (in Chinese, with an English abstract).

Appendix A

Workshop Program and List of Participants

Sponsored by

Australian Centre for International Agricultural Research (ACIAR)
International Water Management Institute (IWMI)
International Rice Research Institute (IRRI)
Wuhan University (WHU)
Zhejiang University (ZJU)

Organized by

Wuhan University (WHU)
Hubei Provincial Bureau of Water Resources (HPBWR)
International Water Management Institute (IWMI)

In Cooperation with

Zhanghe Project Administration
China Rural Water and Hydropower Editorial Department

Main Schedule and Related Events

March 23 (Fri)	15:00–17:00	Presidium meeting at the WHU guest house
March 24 (Sat)	**Morning**	**Chairman: Prof. Wu Peijung,** **(Vice President of WHU)** **Prof. Mao Zhi**
8:30–9:30		Opening Ceremony: Prof. Liu Jingnan, Vice President of WHU; Prof. Feng Guangzhi, Chairman of CNCID, Mr Wu Kegang, Director General of Hubei Provincial Bureau of Water Resources; DG of Dept. of Rural Water Management, Ministry of Water Resources;
9:30–10:00		Photographing and break
10:00–10:30		Overall review of the project by R. Barker
10:30–10:50		Question and discussion
10:50–11:30		Lessons and experiences from ZIS by C. Chen
11:30–11:45		Question and discussion
12:00		Lunch
March 24 (Sat)	**Afternoon**	**Chairman: Prof. Huang Jiesheng**
14:00–15:30		Presentations of Subproject 1: • Dr. G.H. Wang • Dr. G.A. Lu • Dr. T. P. Tuong
15:30–16:00		Question and discussion
16:00–16:15		Tea break
16:15–17:45		Presentations of Subproject 2: • Dr. David Molden • Mr. R. Loeve • Mr. Dong Bin.
17:45–18:15		Question and discussion
18:30		Dinner
March 25 (Sun)	**Morning**	**Chairman: Dr. Ian Willett**
8:30–10:00		Presentation of Subproject 3: • Dr. Hong Lin. • Ms P. Moya
10:00–10:15		Tea break

10:15–10:45		Question and discussion
10:45–11:45		Comments and review by Dr. Ian Willett
12:00		Lunch
March 25 (Sun)	**Afternoon**	**Start-up meeting of the new project** **Chairman: Dr. To Phuc Tuong**
13:30–13:45		General introduction by Dr. Randolph Barker,
13:45–14:15		Subproject 1: Field-scale investigations
14:15–15:00		Subproject 2: General introduction of up-scaling, plus water accounting
15:00 – 15:15		Tea break
15:15 – 16:00		Subproject 2: Up-scaling, Modeling
16:00 – 16:40		Subproject 3: • Irrigation groups and water pricing • Substitutional aspects
16:40 – 17:00		Subproject 4: Extension (Li Yuanhua)
17:00 – 17:30		General discussion, Kick off
18:00		Dinner

List of Names of Participants

Name	Organization	Position	E-mail
Ian Willett	ACIAR	Research Program Manager, Land & Water Resources	willett@aciar.gov.au
Donna Brennan	ACIAR	Research Program Manager, Agricultural Policy Program	Brennan@aciar.gov.au
Liz Humphreys	CSIRO	Research Group Leader, CSIRO Land & Water	Liz.Humphreys@grf.clw.csiro.au
Shahbaz Khan	CSIRO	Senior Research Scientist	Shahbaz.Khan@grf.clw.csiro.au
Steve Beare	ABARE	Economist	
Anna Heaney	ABARE	Economist	
Hector M. Malano	University of Melbourne	Associate Professor, Director, International Technologies Centre; Vice President, ICID	h.malano@devtech.unimelb.edu.au
Hugh Turral	University of Melbourne	Research Fellow	
Randolph Barker	IWMI	Principal Researcher, IWMI	r.barker@cgiar.org
David Molden	IWMI	Research Leader, Irrigation & Water Resources	d.molden@cgiar.org
Ian Makin	IWMI	Research Leader, Design & Operation	i.makin@cgiar.org
Ronald Loeve	IWMI	Associate Expert	r.loeve@cgiar.org
Wang Jinxia	IWMI	Economist	j.wang@cgiar.org
To Phuc Tuong	IRRI	Water Management Engineer	t.tuong@cgiar.org
Bas Bouman	IRRI	Water Scientist	b.bouman@cgiar.org
David Dawe	IRRI	Economist	d.dawe@cgiar.org
Piedad Moya	IRRI	Associate Scientist	p.moya@cgiar.org
Romeo Cabangon	IRRI	Assistant Scientist	r.cabangon@cgiar.org
Feng Guangzhi	Ministry of Water Resources (MWR)	Director General, Department of Rural Water Management, MWR	
Li Yuanhua	NCIDD	Deputy Director General, NCIDD	yuanhli@yahoo.com
Li Wanhong	National Nature Science Foundation of China	Director of Division, Hydraulic Engineering, Department of Materials & Engineering, NSFC	

Wu Kegang	Hubei Provincial Water Resources Bureau (HPBWR)	Deputy Director, HPBWR	
Zhou Hankui	Hubei Provincial Water Resources Bureau (HPBWR)	Director, Division of Reservoir HPBWR	
Jiang Yansheng	Hubei Provincial Water Resources Bureau (HPBWR)	Deputy Director, Division of Foreign Science & Technology Cooperation, HPBWR	yshjiang@public.wh.hb.cn
Wang Guanghuo	Zhejiang University	Professor	Ghwang@mail.hz.zj.cn
Wang Zhongqiu	IRRI-China Liasion Office		Zhqwang@public2.east.cn.net
Lu Guoan	Huazhong Agriculture University	Associate Professor	guoanlu@public.wh.hb.cn
Xu Zhanguo	Editorial Department of “China Rural Water and Hydropower”	Director, Editorial Department	
Zhao Jinghe	ZID	Director General, ZID	
Cheng Chongde	ZID	Senior Engineer	
Zhang Shijiu	ZID	Deputy Director, Department of Water Allocation, ZID	
Zhang Xiaotian	ZID	Director, Trunk Canal, ZID	
Shu Wu	ZID	Director, No.4 Main Canal, ZID	
Wang Jianzhang	ZID	Director, TL Experiment Station, ZID	
Zhang Zhichuan	Henan Provincial Institute of Water Resources Research	Deputy Director, Institute of Water Resources Research	zzcsks@371.net
Guo Mao	Department of Water Division, Yellow River, Kaifeng City	Deputy Director, Department of Water Division, Yellow River, Kaifeng City	
Wu Junpei	Wuhan University	Professor and Vice President, WHU	

Liu Jingnan	Wuhan University	Professor and Vice President, `WHU	
Peng Yuanjie	Wuhan University	Professor and Director, Department of International Cooperation, WHU;	
Zhou Chuangbing	Wuhan University	Professor and Director, Department of Science & Technology, WHU	
Zhong Yexi	Wuhan University	Professor and Director, Department of Hi-Tech Industrial Development, WHU	
Ding Hui	Wuhan University	Professor and Deputy Director. Department of Hi-Tech Industrial Development	
Xu Zhifang	Wuhan University	Professor, Department of Irri. & Drain. Engineering and Vice President, Honour, ICID	zfxu@wuhee.edu.cn
Mao Zhi	Wuhan University	Professor, Department of Irri. & Drain. Engineering	mao_zhi@163.net
Martin Parkes	Wuhan University	Foreign Expert	martin@wuhee.edu.cn
Tan Guangming	Wuhan University	Professor and Director, College of Water Resources	
Huang Jiesheng	Wuhan University	Professor and Deputy Director, College of Water Resources	jshuanga@public.wh.hb.cn
Luo Jinyao	Wuhan University	Professor, Department of Irri. & Drain. Engineering	luojyly@hotmail.com
Shao Dongguo	Wuhan University	Professor and Deputy Director, Department of Irri. & Drain. Engineering	
Cui Yuanlai	Wuhan University	Associate Professor, Department of Irri. & Drain. Engineering	cuiyl@fm365.com
Hong Lin	Wuhan University	Associate Professor, Department of Irri. & Drain. Engineering	honglin@public.wh.hb.cn
Dong Bin	Wuhan University	Lecturer, Department of Irri. & Drain. Engineering	dongbinh@public.wh.hb.cn
Huang Hansheng	Wuhan University	Engineer, Department of Irri. & Drain. Engineering	
Chen Xiuhong	Wuhan University	Lecturer, Department of Irri. & Drain. Engineering	

Appendix B

Related Publications

Other publications related to this project are listed below.

Chinese Center for Agricultural Policy (National Academy of Sciences) and IWMI: 2001. *China Water Resources Newsletter*. January 2001. Water resources in China.

Dong, B.; Ronald Loeve; Li Yuanhua; Chen Chongde; Deng Li; and David Molden. 2001. Water productivity at Zhanghe Irrigation System at different scales. Paper presented at the 52nd International Executive Council and 1st Asian Regional Conference, ICID, Seoul, Korea, 16–21 September 2001.

Hong, L.; L. H. Li; L. Deng; C. D. Chen; D. Dawe; R. Loeve; and R. Barker. 2000. Analysis of changes in water allocations and crop production in the Zhanghe Irrigation System and District, 1966 to 1998. *IWMI Annual Report 1999–2000*.

Guoan, Lu; Li Yuanhua; and Sha Zongrao. 2000. Influence of water saving irrigation on nutrient of potassium content for rice. *China Rural Water and Hydropower,* No. 2, Feb. 2000 (in Chinese)

Guoan, Lu; and Li Yuanhua. 2001. Influence of water saving irrigation on nutrient of phosphorus content for rice. *Irrigation and Drainage,* No. 1, March. 2001 (in Chinese).

Li, Deng; Wang Xiaolion; and Hong Lin. 2000. Influence of water saving irrigation on farmers' incomes and expenses. *China Rural Water and Hydropower,* No. 9, Sept. 2000 (in Chinese).

Yuanhua, Li; Jiang Guojiang; Chen Chongde; Dong Bin; Hong Lin; and Deng Li. 2001. Experiences and enlightments of efficient water use in ZIS in China. *Water*, No. 1, 2001 (Monthly Journal) (in Chinese).

Postal Address
P O Box 2075
Colombo
Sri Lanka

Mailing Address
127, Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Telephone
+94-1-787404, 784080

Fax
+94- 1-786854

E-Mail
iwmi@cgiar.org

Website
http://www.iwmi.org

IWMI
International
Water Management
Institute

FUTURE HARVEST
IWMI is a Future Harvest Center
supported by the CGIAR

ISBN 92-9090-465-8