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WATER PRODUCTIVITY IN ZHANGHE IRRIGATION SYSTEM AT DIFFERENT SCALES

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Abstract

Zhanghe Irrigation System (ZIS), located in the Yangtze Basin in Hubei Province in middle China, provides irrigation facilities for approximately 160,000 ha of land. The main water supply is the Zhanghe Reservoir, constructed between 1958 and 1966. ZIS farmers were the dominant users of the reservoir supply until the 1980s. Then from 1978 to 1988 there was a sharp decline in the amount of water supplied to agriculture due to increasing demands from cities, industries, and hydropower generation utilities. In spite of water moving out of agriculture into other uses, rice production at ZIS has only slightly declined because of increases in the productivity per unit of water supplied to agriculture. This paper explores factors behind the increase in water productivity at ZIS.

At Zhanghe, on-farm water saving irrigation (WSI) techniques are widespread amongst farmers. It is hypothesized that WSI practices have been a major factor enabling the transfer of water to other higher-valued uses without significant loss in crop production. A water accounting methodology developed by IWMI was applied to ZIS to evaluate the status of water use and productivity. To better understand the mechanism for water savings, field studies and historical records were analyzed at different scales ranging from field to sub-basin levels. This paper explores how practices at the farm level are upscaled in ZIS. By better understanding the "scaling up" of water saving practices, important insights can be gained that will contribute to improved design and management of irrigation for water stressed environments.

At the sub-basin scale, 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 and a considerable increase in water productivity over time. At the field scale, farmers practicing WSI techniques are very effective in converting water deliveries to crop evapotranspiration, and limiting seepage and percolation. At a larger "mezzo" scale, other factors including reuse become important. By performing the analysis at various scales, we

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demonstrate that there are several practices that ultimately influence water savings at a sub-basin scale. These practices include on-farm WSI practices, water recycling, capturing of other sources of water, ample storage, precise canal operations, and incentives for farmers and system operators to produce more rice with less water.

Introduction

Growing more rice with less water is one of the major challenges of the 21st Century. Rapidly increasing water demands from cities, industries, and environmental uses will put a strain on water resources in many river basins. 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 fresh water sources, because of the difficulties encountered with new large infrastructure development work; but also in many cases, 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.

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 is well advanced. Many practices have been developed for farmers to deliver less water to their fields, and are collectively known as water saving irrigation (WSI) practices (Wang, 1992; Mao, 1993; Peng et al., 1997). For example, intermittent submerged irrigation (See Fig. 1) has been spread in south China (Li et al.1999). This practice is being implemented on large scales such as in ZIS, which serves about 160,000 ha of irrigated land, intensively cultivated with rice. A question of global interest is whether this practice has led to water "real" savings, which can be transferred to other agricultural and non-agricultural 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.

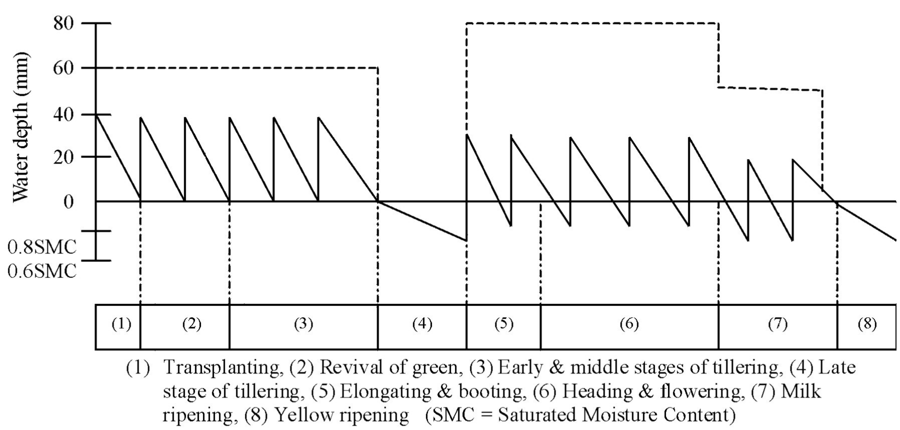

Fig. 1 Graphical description of intermittent submerged irrigation regime (Mao et al., forthcoming).

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" (Guerra et al.1998). They are addressing some of the technical and institutional issues underlying the successful application of WSI techniques—for example fertilizer use, the financial costs and benefits to farmers, the implications of the eventual large-scale adoption of these techniques on water savings, and water productivity increases. This is particularly important for China, where per capita fresh water availability is among the lowest in Asia and still declining.

The objective of this paper is to present information from field studies and historical records at different scales ranging from field to sub-basin levels that helps us better understand issues of scale in rice irrigated areas. This paper explores factors behind the increase in water productivity at ZIS. We will first present some basic concepts of water savings, basic issues of scale, then show how practices at the farm level are upscaled in ZIS. By better understanding the "scaling up" of water saving practices, important insights can be gained on the design and management of irrigation that will lead to transferable water savings.

Water Savings

One difficulty in communicating about water saving is that "water savings" 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 farmers have to pay for water, either by paying energy costs of providing water, or by paying a service provider, there may sufficient incentive to apply less water. Another example is when water a limited supply of water is rationed, farmers have an incentive to keep their production levels high with a limited amount of water. In these farm level cases, "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 a basin scale. In many basins of the world, there are growing demands for good quality water for non-agricultural uses – the environment, cities, industries. Plus 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, and there is pressure to meet other demands first, then let agriculture have the remaining drops. At a basin scale, a common interest is in reducing the total amount of water depleted by irrigated agriculture yet maintain or increase production. At this scale we consider the total amount of basin resources and how they are allocated across sectors and uses in time and in space across the basin. 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, is 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 1ha to 100ha up to more than 10,000ha other uses of water start to interact more with rice water use when the scale of interest grows. These concepts are illustrated using the Zhanghe Irrigation System.

Methods

The main research site of this paper is the Zhanghe Irrigation System (ZIS). ZIS lies within the Yangtze River Basin and is bounded by the Han River on the Northeast Side and the Yangtze River on the Southwest. It is one of the typical large-size irrigation systems in China with a total area of 5540 km^2 of which about 160,000 ha is irrigated area. Many water bodies fill the landscape in this water rich environment. 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 spite of apparent abundance, saving water in agriculture is extremely important to meet other growing needs.

The Zhanghe reservoir, built on a tributary of the Yangtze River, supplies most of the irrigation water in ZIS. The reservoir was designed for multipurpose uses of irrigation, flood control, domestic water supply, industrial use and hydropower generation.

In 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 7000km. A large irrigation network including large, medium and small-size reservoirs for purposes of storing, diverting and withdrawing water have been established. The main crops are rice, winter wheat, sesame oil and soybean with paddy fields occupying about 80% of the total irrigation area.

Since the 1980s, a rehabilitation and improvement program has been carried out to improve the performance of ZIS. In addition to infrastructure, the program has included popularization of WSI techniques, canal lining, volumetric charging, drainage water reuse and other management innovations. Through this research, we are testing the commonly heard assumption that the popularization of WSI technique, one of the elements in the rehabilitation program, has enabled water managers to transfer water away from agriculture to other higher-valued uses without significant loss in crop production.

Study site

For this research we considered water use, savings and productivity at three scales: a micro scale at the size of a field or a set of fields, a mezzo scale covering 300 to 600 ha, and a macro scale covering the entire ZIS area. The scales were chosen to capture the scale effects of farm scale interventions.

At the micro scale data was collected on farmers' fields to study actual practices. Two sites were selected to represent situations where WSI is said to be widely practiced; and another site where WSI is said not to be so common. Within both sites data was collected at the micro scale and at the mezzo scale. One site was selected near the Tuanlin Irrigation Experimental Station (with WSI), about 20km southeast of the Zhanghe Reservoir. Another one is located in Wenjiaxiang Township (without WSI), about 35km northeast of the Zhanghe Reservoir. All flow components and rice yields were quantified. Long-term meteorological data from the Tuanlin Irrigation Experimental Station was used for computing the reference evapotranspiration.

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 286.9 ha of which about 41% are paddy fields. The Wenjiaxiang pilot area is supplied by the East Branch of the Fourth Main Canal and located at the tail end of the canal. The total area is 606.4 ha of which about 28% are paddy fields. The northern part of Wenjiaxiang pilot 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 end May to early September. Upland crops, such as maize, soybean, are also planted during middle rice growing season but are normally not irrigated.

At the macro scale, we considered the entire Zhanghe Irrigation System. Secondary data was used on water releases and crop production to obtain an initial indication on water savings and the productivity of water.

The water accounting procedure developed by IWMI (Molden, 1997 and Molden and Sakthivadivel, 1999), based on a water balance approach, was used to study water savings. The water accounting system was considered at different spatial scales: field, mezzo, sub-basin or basin. The water accounting procedure classifies water balance components based on how the water is used and the outflow. Water accounting indicators are presented in the form of fractions and in terms of productivity of water.

Results

Field Scale – Farmers' Fields: The summary of water accounting at field scale within the two mezzo sites in 1999 and 2000 is shown in Table 1. The time period for water accounting was from land preparation (about 20 May) to 31 August. In the two years, rice yields in Wenjiaxiang (non WSI) were a little higher than that in Tuanlin (WSI), but irrigation water use was much higher compared to Tuanlin, leading to higher average values of $WP_{irrigation}$ for Tuanlin. Values for WP_{ET} were similar between sites for both years.

The process fraction of gross inflow was also quite high ranging from 0.66 to 0.93 in both areas indicating care with both irrigation 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 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.

Mezzo scale: The water accounting components and indicators for the two mezzo-scale sites in 1999 and 2000 are summarized in Table 2. The time period for water accounting was from land preparation (20 May) up to the end of harvesting (1999: 20 September, 2000: 10 September in 2000). Meteorological data is from the Tuanlin Irrigation Experimental Station and potential evapotranspiration was calculated using the Penman-Monteith equation. Inflow and outflow components were measured at the boundaries of the study area.

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

Table 1. Water accounting at field scale in Tuanlin and Wenjiaxiang[1]

	Year 1999		Year 2000	
	Tuanlin	Wenjiaxiang	Tuanlin	Wenjiaxiang
Gross area (m^2)*	7607	7788	7606	7788
Net area (m^2)	7445	7577	7445	7577
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
Paddy yield (kg/ha)	7890	8610	7430	7770
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
* Note: Gross area is the net area plus the area occupied by bunds.
** Note: The total outflow includes drainage and deep percolation.

For the two mezzo sites the depleted fraction of gross inflow ranges from 0.09 to 0.20 for the two sites much lower than at the field scale (that is 9% and 20% of the rain plus irrigation is depleted by evaporation by all uses). The percentage of paddy field to total area for the two sites is about 41% at Wenjiaxiang and 28% at Tuanlin. In Tuanlin and Wenjiaxiang rice consumes 55% and 42% of the depleted water respectively. 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.

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 agriculture, cities and industries downstream.

Table 2. Water accounting at mezzo scale in Tuanlin and Wenjiaxiang

	Year 1999		Year 2000	
	Tuanlin	Wenjiaxiang	Tuanlin	Wenjiaxiang
Total area (ha)	287	606	287	606
Paddy field area (ha)	117	179	117	167
Inflow				
Adjusted surface inflow (total area) (mm)*	340	370	582	441
Rainfall (mm)	379	379	463	408
Gross inflow	719	749	1045	849
Irrigation duty (for rice) (mm)	755	1065	1199	1523
Paddy yield (house hold survey) (kg/ha)	7430	8440	6330	6440
Paddy yield (average of micro sites) (kg/ha)	7890	8610	7430	7770
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

* Surface inflow was adjusted by subtracting outflow from the canal that transported water through the mezzo site that was considered committed for downstream uses.

Note: Yield data was obtained from a socio-economic survey with sample size of thirty except for Tuanlin in 1999 where the sample size was 22 households (2 outliers were eliminated). Yield data was also obtained from the micro-sites in each area, however it was decided to use the data from the household survey since the sample size is bigger and it is spatially better distributed over the mezzo sites.

[*] Depleted fraction of gross inflow is calculated as the amount evaporated by all uses divided by the sum of rain plus irrigation, the process fraction of gross inflow is rice evapotranspiration divided by rain plus irrigation; the process fraction of depleted water in this case is rice evapotranspiration divided by evaporation from all sources.

Compared to the indicator at field scale, $WP_{irrigation}$ values at 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?

Sub-basin scale: Similar water balance data is not yet available for the entire sub-basin (including the irrigation system, non-irrigated crops, cities and industries). Nevertheless, from existing secondary data, it is possible to obtain an indication of scale effects regarding the productivity of water. Fig. 2 shows the long-term data on irrigation water from the Zhanghe Reservoir, rice-irrigated area and rice production in ZIS. The share of water supplied to irrigation was dominant until 1980s. Afterwards 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 paddy area directly irrigated by the reservoir declined over the years. During the 1990s the area was reduced by about 20% from the level in the 1980s (See Fig. 2). Despite the decline in Zhanghe reservoir releases for irrigation rice production has continued to rise until the 1990s, where there is a slight reduction in the past 10 years (See Fig. 2) due to the decrease in rice areas. The major factors contributed to 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 Zhanghe reservoir has shown an upward trend as shown in Fig. 3. 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 was 2.61 kgm^{-3} in the last period 1989-98 shows it has tripled compared to the first period[†].

Conclusions

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

[†] 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 Zhanghe reservoir water, not of all the sources of water within the irrigated area.

The water accounting result at field scales shows that the farmers are effectively able to capture rainfall and irrigation water supplied to fields and convert this into productive crop evapotranspiration. The process depletion (rice ET) fraction of gross inflow (rain + irrigation) at field level commonly is more than 65%. The production per unit of irrigation water was typically higher for Tuanlin where farmers practice WSI.

At 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 level compared to the field level. This is explained by the considerable runoff from non-rice land at the two 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.

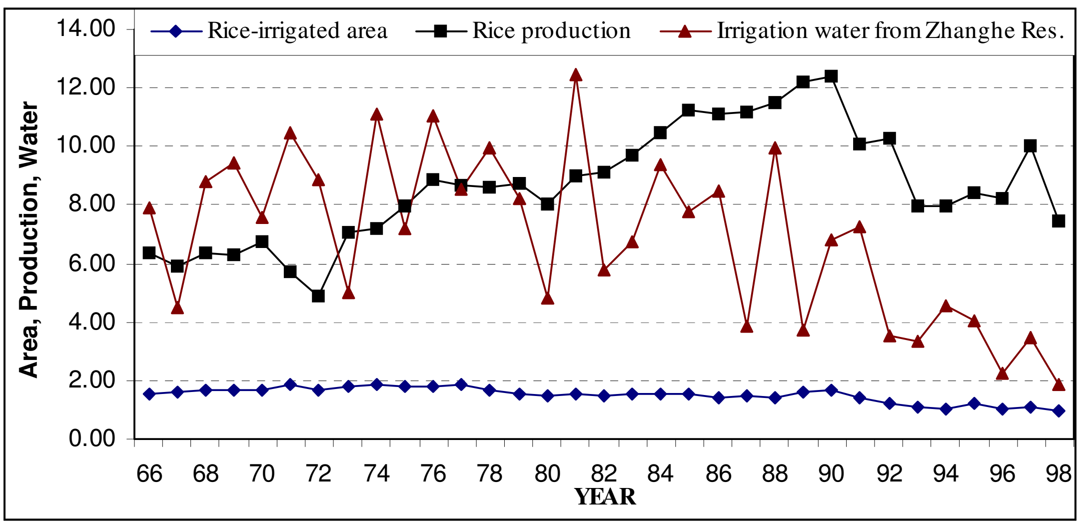

Fig. 2 Annual rice-irrigated area (10^5ha), rice production (10^8kg) and irrigation water (10^8cubic meters) from Zhanghe Reservoir (1966-1998)

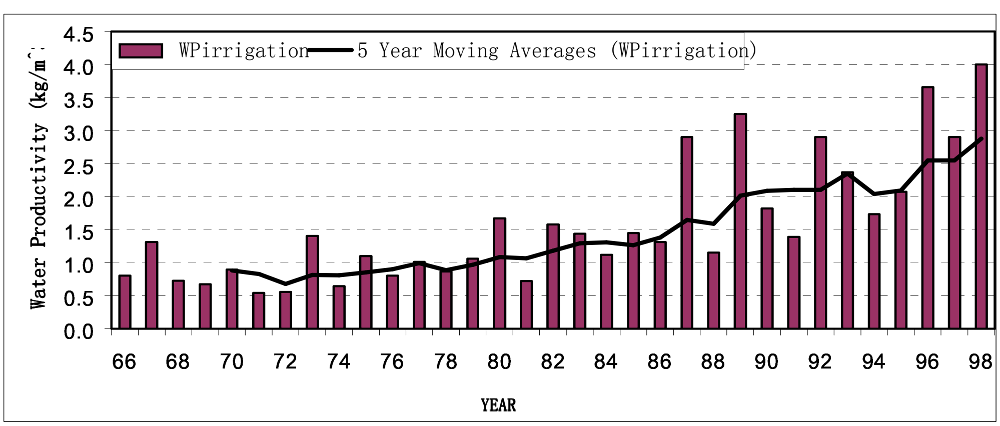

Fig. 3 Trend of $WP_{irrigation}$ (1966-1998)

The macro (sub-basin) level shows an increase in water productivity compared to the mezzo scale. Here it becomes clear that ZIS with its possibilities of capturing rainfall and run-off in all the reservoirs within the system is very effective for us in capturing and using water for productive use. Water capture and reuse are of major importance at this level of analysis.

The macro (sub-basin) level analysis indicates there is an increase in the productivity of water over time at the sub-basin scale and real water saving takes place. Water productivity of irrigation supplies increases from the mezzo scale and 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 WSI practices, a shift in the cropping pattern from two to one crops of rice, volumetric charging, better delivery system management, and water reuse - primarily from the many small and medium sized reservoirs scattered throughout the area. On-farm WSI 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 sized 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 paddy fields are captured and used again replacing the need to release Zhanghe reservoir water. System level water managers can thus keep the water high in the system 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.

Because water savings in rice areas is such an important task it is important to gain further understanding of the strategies employ 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. This study demonstrates that a combination of factors can be important in achieving real water savings.

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