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Water-Saving Irrigation for Rice

SWIM
System-Wide Initiative
on Water Management

Proceedings of an
International Workshop
Held in Wuhan, China
23–25 March 2001

R. Barker, R. Loeve, Y. H. Li
and T. P. Tuong, editors

PROCEEDINGS

CGIAR
IWMI International Water Management Institute
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Wuhan University of Technology
ZHEJIANG UNIVERSITY

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Contents

Foreword

This report presents the proceedings of a workshop held at Wuhan University, China during March 23–25, 2001. The overview discusses the background and research objectives, and summarizes the research results of the six chapters, which discuss the procedures and findings of 2 years of research. The research was conducted by a team of scholars from the Universities of Wuhan and Zhejiang in China, from the International Rice Research Institute (IRRI) and from the International Water Management Institute (IWMI) with the assistance of the staff of the Zhanghe. The workshop marked not only the end of the 2-year project (1999–2000) but also the beginning of a 4-year follow-on project (2001–2005), both projects funded by the Australian Center for International Agricultural Research (ACIAR).

The project was initiated under the Systemwide Initiative on Water Management (SWIM). It has been a truly collaborative undertaking with each of the institutions bringing different expertise to the research effort. The names of authors of the papers together with their designations are listed below for each institution:

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Abbreviations and Acronyms

ACIAR	Australian Centre for International Agricultural Research
ABARE	Australian Bureau of Agriculture & Resource Economics
AWD	Alternate wetting and drying
CGIAR	Consultative Group on International Agricultural Research
CIMMYT	Centro Internacional de Mejoramiento de Maize y Trigo [The International Maize and Wheat Improvement Center]
CSIRO	Commonwealth Scientific and Industrial Research Organization
ET	Evapotranspiration
FC&AD	Flood control and anti-draught
HAU	Hua Zhong Agricultural University
HPBWR	Hubei Provincial Bureau of Water Resources
IRRI	International Rice Research Institute
IWMI	International Water Management Institute
K	Potassium
LAI	leaf area index
LIS	Liuyuankou Irrigation System
mcm	million cubic meters
MWR	Ministry of Water Resources
N	Nitrogen
NCIDD	National Center of Irrigation and Drainage Development
NSFC	National Nature Science Foundation of China
P	Phosphorus
SMC	Saturated moisture content
SSD	Soil Sciences Division
SWIM	Systemwide Initiative on Water Management
TL	Tuanlin
WHU	Wuhan University
WJX	Wenjiaxiang
WP	Water productivity
WPF	Water production functions
WSI	Water-saving irrigation
ZJU	Zhejiang University
ZID	Zhanghe Irrigation District
ZIS	Zhanghe Irrigation System

Overview

R. Barker, Y. H. Li and T. P. Tuong

Background

The demand for freshwater for industrialization and domestic urban needs is growing rapidly throughout Asia. Less water will be available for agriculture and for rice, the crop that consumes the largest amount of freshwater. There is an urgent need to find ways to "grow more rice with less water."

China is severely water-short. With one of the most intensive rice-irrigation systems in the world, Chinese scientists have been exploring ways to save water in rice production. In November 1997, the IRRI-China Dialogue approved a concept note on "Achieving Economical and Sustainable Water-Efficient Irrigation in Rice-Based Systems in China," which became the starting point for the development of this project. In July 1998, the Systemwide Initiative on Water Management (SWIM) sponsored a workshop held at IRRI to discuss the potential for producing more rice with less water in irrigated systems (Guerra et al. 1998). At that time, IWMI agreed to join IRRI and Chinese colleagues in the development of this project.

This report describes the research activities of the project, the findings and the dissemination of results. There are two appendixes—appendix A, the program for the end-of-project workshop and list of the names of participants, and appendix B, for related publications.

Research Objectives

The ultimate goal of this and the follow-on project is to develop irrigation-management strategies and techniques for rice-based systems that are high in water efficiency and productivity, are cost-effective and can be implemented over large areas of China and other countries.

The specific objectives of the research were to

- quantify the impact of water-saving irrigation (WSI) on water, crop yield, water productivity and on fertilizer use efficiency
- assess the financial costs and benefits of these technologies to farmers
- develop and test a methodology to study irrigation-system-wide and basin-wide implications of on-farm WSI innovations in order to understand the degree to which

their large-scale adoption will lead to system-wide and basin-wide water savings and water productivity increases

- contribute to the acceleration of the adoption of innovation of irrigation-water management to other rice-planting regions of China and other countries

Description of the Research

The bulk of the research was conducted in the Zhanghe Irrigation System (ZIS) in the Hubei Province, approximately 200 km west of Wuhan, China. Field experiments were also conducted at Jinhua in the Zhejiang Province. The focus was on a water-management technique currently being adopted in some parts of China known as the *alternate wetting and drying* (AWD). Sites were chosen in two townships in ZIS. In one, Tuanlin (TL), AWD was said to be widely practiced, while in the other, Wenjiaxiang (WJX), AWD had not been formally introduced. These mezzo sites were chosen in such a way as to be able to measure the flow of water into and out of the sites during the rice-cropping season.

The research was conducted over two rice-growing seasons in three subprojects. Subproject one involved the conduct of controlled field experiments at the TL site and at Jinhua in the Zhejiang Province to determine the effect of AWD, the timing of fertilizer applications, and their interactions on yield and water productivity. Under Subproject two, surveys were conducted for 30 farms within TL and WJX mezzo sites to identify the farm water-management and other practices and to measure costs and returns. Under Subproject three, the water accounting methodology developed by IWMI was applied on 6 of the 30 farms surveyed, representing micro-scale sites and on the two mezzo sites, TL and WJX.

To supplement the above research, two additional studies were conducted. First, an analysis was made of the trend in the allocation of ZIS water to irrigation and other sectors and of the trends of crop production, yields, and irrigation water productivity in the Zhanghe Irrigation District (ZID) over the period 1966–1998. Second, a study was made of the procedures and rules followed in the management of irrigation water and collection of irrigation fees within ZIS, tracing the path of decision making and fee collection activities from reservoir to farm level.

The end-of-project, *International Workshop on Water-Saving Irrigation for Paddy Rice,* was held at the Wuhan University during March 23–25 and involved about 50 participants (see appendix A). The results of the research were presented and discussed and plans made for the publication of the workshop proceedings (see appendix B for related publications).

Research Results

Chapter 1 in this report describes the research, development and application of WSI for rice in various parts of China drawing on the Chinese literature. Chapters 2 and 3 discuss the changes in water allocations over time and the operation of ZIS. The remaining three chapters present the findings from each of the research subprojects.

Chapter 1. Research and Practice of WSI for Rice in China

China has exerted significant effort in developing and applying water-saving practices in rice-irrigated areas. In response to increased competition for water and the importance of rice production, the Chinese have invested in research on WSI practices. They have supported policies and practices that promote real water savings. Farmers have adapted these practices on a widespread basis and there are many success stories about water savings in China. There is evidence that the traditional practice of irrigating rice has changed and that yields and productivity of water have increased due to these practices.

Unfortunately, the documentation of research and practice is mostly in the Chinese language, making it difficult for others from outside of China to learn from the Chinese experience. The objective of this paper is to review the Chinese experience with WSI. The paper provides a historical background on research efforts into WSI and an overview of theoretical research done in China, explains how WSI techniques were introduced in China, and suggests areas of future needs in China. The lack of research on the impact of WSI practices at the system and basin levels (a key focus of our study) is noted.

Chapter 2. Analysis of Changes in Water Allocation and Crop Production, in ZIS and ZID, 1966–98

Water in the Zhanghe reservoir began to be diverted from irrigation to other uses in the 1970s. This seems to have presented few problems at first since there was more than ample water to serve the command area. Following the end of the Cultural Revolution in the 1970s, significant reforms took place that had a positive effect on both water productivity and crop production. Volumetric pricing was introduced. New pump stations were built. Medium and small reservoirs were restored and expanded. Introduction of improved varieties and increased use of chemical fertilizers led to a sharp increase in rice yields. Due to improved water-management and crop-production practices, in the period 1979–88, rice yields increased by 66 percent and rice production grew by 45 percent over the 1966–78 period.

Compared with the 1980s, however, the 1990s witnessed a drop in water supplied to agriculture by ZIS of more than 50 percent. For the same period, area irrigated to rice in ZID fell by 12 percent but rice production fell only by 6 percent. During this period a concerted effort was made to save water and increase water productivity to minimize the decline in production and the practice of AWD was introduced. Other factors mentioned above, including the steady increase in rice yields, helped offset the production decline. Over the past year (2000) water allocation for power generation was reduced to permit an adequate supply of water for irrigation.

The demand for water for nonagricultural purposes will continue to grow. Scope for further increases in water productivity appears limited. Thus, ZIS will almost certainly continue to be faced with decisions on the allocation of limited supplies of water and trade-off among competing uses. A major objective for future research will be to identify more clearly the contribution of various factors to increases in water productivity at farm, system and basin levels.

Chapter 3. Operation of the Zhanghe Irrigation System

We explored the water management of ZIS, tracing key decision points for water allocation and distribution. We outlined the kinds of arrangements made at key points from the reservoir to farmers' fields and then considered the mechanisms and flow of money from farmers' fields to reservoir operators for the payment of services. This has important implications for the successful implementation of WSI practices.

At the beginning of the irrigation season (end March, beginning April) the Zhanghe Irrigation Administration Bureau makes a long-term forecast allocation plan for ZIS based on the area to be irrigated, on weather forecasts and on the storage in the main reservoir. The water allocation for each main canal is based on experience and the requests come from the water users in the command area. However, during the flood season, the Hubei Provincial Government has the power to decide on the amount of water to allocate to hydropower and flood-control release. As much water as possible will be stored to meet the demand for water for all sectors. However, irrigation has priority over hydropower.

While farmers do order water, by and large, reservoir operators make the decisions on water releases. The timing of the water releases from the reservoir depends on the available storage, on rainfall, and on an overall view of when crops need water. But release dates are almost the same every year. There are usually about three to five releases a year to any given branch canal. However, the third main canal (location of TL site) receives water only twice a year. This is considerably less than what the fourth main canal (location of WJX site) receives. This difference is explained by better local resources (reservoirs and ponds) in the third main canal area and by lighter soils in some parts of the fourth main canal area.

The ponds and small reservoirs located within the command area allow farmers to obtain water on demand. The Provincial Finance and Pricing Control Bureau determines the price per unit of water for each alternative use—irrigation, industry, municipal and hydropower. The water user groups or villages pay the water fee to the ZIS main canal section on a volumetric basis.

Group or village heads prorate the charge to farmers, based on area, but farmers are well aware that, if the village or group uses less water, the charge is reduced. For this reason, farmers minimize the use of ZIS water and maximize the use of rainwater, drainage water (which is for free), and water from other local sources.

Chapter 4. Impact of AWD on Rice Growth and Resource Use Efficiency

The objective of this study was to quantify the impact of AWD irrigation and timing of N fertilizer application on rice growth, water use, water productivity and fertilizer use efficiency. Experiments were carried out in the middle rice-crop season in 1999 and 2000 at TL in ZIS and in the early and late rice crops in 1999 and 2000 at Jinhua in the Zhejiang Province.

Yield differences between AWD and continuous flooding treatments were not significant at 5 percent level at either site or in either year. Thus, no yield was lost in the application of AWD. However, AWD reduced the consumption of irrigation water compared with continuous flooding. The differences were statistically significant only in 2000 when rainfall was low and evaporation demand was high. Water productivity in terms of irrigation water was about 5–35 percent higher under AWD than in continuous flooding, but differences were significant only in the year 2000. The productivity of the total water supply (irrigation plus rainfall) for AWD and continuous flooding was not significantly different. The results also imply that mid-season drainage and periodic drying are not prerequisites for high yields. This gives farmers more flexibility in the application of AWD. For example, in years with high rainfall, farmers may decide to store more rainfall and, therefore, can further reduce the amount of irrigation water consumed in subsequent dry spells.

There were no significant water-nitrogen interactions at either of the experimental sites. This implies that the same N-fertilizer management strategies for conventional flooded irrigation can be applied to AWD. Increasing the number of split nitrogen applications from four to six times compared to the farmer practice of two splits increased the N uptake but not the grain or biomass yield. This may reflect the inability of the popular rice varieties to convert increased N uptake into grain.

The real productivity gain from the implementation of AWD depends on the benefits and costs incurred from the “saved” irrigation water. The saving should allow ZIS to reallocate more water from irrigation to higher-value uses. But the savings may also result in a loss of water for users downstream of the sites. This was one of the issues posed for Subproject three.

Chapter 5. Comparative Assessment of On-Farm Water Management Strategies in ZIS

Sites were selected in TL and WJX townships and a sample of farmers was surveyed to compare the performance of those adopting AWD and those continuing to practice continuous flooding. TL represented an area where AWD was thought to be widely adopted by farmers, while WJX represented a site where AWD had not been formally introduced. Data were collected from 30 farms in each site to make an economic comparison in terms of rice production and profitability and water-management practices including the degree of AWD adoption.

Most input costs for growing rice did not differ significantly between sites. However, farmers in WJX paid more for seeds and water, applied more labor and obtained a higher rice yield. Their return over paid-out costs was higher but their net return (including cost of family labor) was lower. However, confirming the results of the experiments, the yields of those practicing AWD and continuous flooding were not significantly different. When one compares the two sites in terms of water management, there was very little difference in frequency of irrigation under different soil-moisture conditions and depth of water applied. The distinction between sites practicing AWD was not as sharp as expected although more farmers in TL practiced AWD. In fact, most farmers do not practice a pure form of AWD or of continuous flooding. However, more farmers in both sites practiced AWD in 2000, when there was a greater shortage of irrigation water than in 1999. Thus, the degree to which farmers are forced to adopt AWD due to reduction in ZIS water releases or due to voluntarily practice of AWD is not clear.

Chapter 6. Water Productivity in ZIS: Issues of Scale

A water-accounting methodology developed by IWMI was applied at different scales—at farmers' fields, at the mezzo scale and, finally, at the irrigation-system level. The micro-scale field studies verified the findings of the experiments and farm surveys that, by using AWD techniques, farmers limited seepage and percolation and increased water productivity.

The production per unit of gross inflow (deliveries plus rainfall) decreased at the mezzo level compared with the field level. This is explained by the considerable runoff from non-riceland at the two sites. However, a considerable amount of the outflow is not wasted but captured and stored in downstream reservoirs for use for irrigation and other purposes. For example, we know from maps, observations and interviews that there is a reservoir downstream that delivers water for irrigation and other uses. Capture of runoff and reuse of irrigation water become important for water saving, as the scale becomes larger.

As discussed earlier, analysis of time-series from ZIS (macro or subbasin level) indicates that there has been an increase in water productivity over time. (This is, of course, different from the spatial scale). Several factors have contributed to the increase in water productivity and one of the most important of them has been the construction of numerous small reservoirs that capture runoff and store water releases from the main reservoir thus facilitating the adoption of practices such as AWD at the farm level.

Through Subproject three, we tested a water-accounting methodology to study irrigation system- and basin-wide implications of on-farm WSI innovations. This methodology was useful in that it enabled us to identify other processes that influence water savings at larger scales such as storage, reuse and capture of rainfall runoff internal to the study area. It also helped us to understand farm practices and the importance of capturing rain at the farm level. We found that, in addition to the micro and mezzo scales, we need larger scales to better understand the degree to which water savings were achieved, and this will be done as a follow-up. The number of measurements required at the mezzo level was more than expected, and makes replication of such research difficult. In other locations, we should be able to identify boundaries where fewer measurements are required. Modeling and remote sensing will be useful to fill gaps where measurements cannot be made and these will be tried in the follow-up project. While there is uncertainty related to errors in measurement, the picture given by the water-accounting method provides some useful information, and was beneficial in generating discussion.

Use of Research

The major achievement of the first phase of the research was the successful testing of methodology, particularly the methodology for scaling up from farm level to system level. A core of collaborators in China has gained experience in interdisciplinary research in water management involving hydraulic engineering, agronomic and economic components. These researchers are involved in the development of a 4-year follow-on project to be initiated in 2001.

Meanwhile, the methodology developed in this study is being utilized in the design of research in two sites, one in the Pakistan Punjab and one in Harayana, India. This research is being carried out collaboratively by scientists from IWMI, CIMMYT, IRRI, and national programs and is financed by the Asian Development Bank through the Rice-Wheat Consortium.

Follow-on Project

A 4-year follow-on project, "Growing More Rice with Less Water " (LWR1/2000/020) has been approved for funding by ACIAR. Under this project research will continue at the Zhanghe site and will be initiated at a new site, the Liuyuankou Irrigation System (LIS) in Kaifeng. This will allow a comparison of the effectiveness of WSI technologies under two very different climatic and water-management situations found in the Yangtze river basin (ZIS) and the Yellow river basin (LIS). The addition of researchers and a research site in the Murray-Darling basin in Australia will strengthen our modeling capacity and, hence, our ability to extend our findings through simulation in other environments.

Literature Cited

Guerra, L. C.; S. I. Bhuiyan; T. P. Tuong; and R. Barker. 1998. *Producing more rice with less water from irrigated systems*. SWIM Paper 5. Colombo, Sri Lanka: International Water Management Institute.

Chapter 1

Research and Practice of Water-Saving Irrigation for Rice in China

Y. H. Li[1]

Introduction

China is the biggest rice-producing country in the world. The planting area of rice is about 31 million hectares and makes up 30 percent of the total planting area of grain crops; the rice production per year is around 185 million tons and accounts for 44 percent of the total grain production in China. On the other hand, the availability of per capita freshwater in China is among the lowest in Asia. On average, there are only 2,260 m^3 of freshwater per year per head, which value is less than a quarter of the average value in the world. The distribution of precipitation in seasons and years is quite uneven and the water resources do not match with the distribution of farmlands. Though it is wet in the south of China, about 90 percent of the freshwater is used for rice production. The water shortage has been the bottleneck for both economic and agricultural development in China. Therefore, the need for more rice with less water is more urgent in China than in many other countries in the world. Increasing attention has been paid to improve irrigation water management of rice fields because of its importance in food production and its huge water use. In recent years, China has pioneered some water-saving policies and WSI techniques for rice production, aiming at increasing water and land productivity.

Traditionally, rice is grown under continuously flooded conditions in rice fields except for a short period of sun-drying at the late stage of rice tillering for adequately meeting the water needs of rice and the efficient supply of nutrients to the crop[2] (Liang 1983). Many studies have indicated that since the middle of the 1980s, significant savings in quantities of water used in traditional rice culture were possible without distinct reduction in rice yield (Fang 1989; Li et al. *Experiment study,* 1994; Tripathi et al. 1986; Zhu 1981; Zhu and Gao 1987). Some WSI techniques have been adopted widely in China (Li 1999; Liu and He 1996; Liu 1998; Mao 1997; Peng et al. 1997; Wang 1992; Xu et al. 1990).

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[2]In China, sun-drying was widely adopted in the late 1960s, so here, the “traditional way” refers to the practice before the mid-1980s. On the other hand, sun-drying was not originally developed for saving water.

In China, the term “WSI” has been used widely for any measure that leads to reducing irrigation water or increasing irrigation water productivity without distinct reduction in crop yield. There are many research papers on WSI for rice and a lot of success stories about application of WSI techniques that result in water savings at the farm level (Li et al. 1998; Li 1999; Li and Cui 1996; Peng et al. 1997; Wang 1992; Wu 1998). However, literature in such research in English is lacking. Such a situation not only limits international colleagues’ understanding of the practice but also affects Chinese scientists’ ability to learn through feedback from the insights of others. The objective of this paper is to describe the formation of the WSI techniques and to summarize the experiences on the WSI for rice in China.

Background of Development of the WSI Techniques for Rice

The experiment and research of WSI started in China in the 1950s (Ding 1961; Li et al. 1964; Xu 1963). But the direct purpose of the research was to improve the illumination and heat conditions of the rice fields and to control the ineffective tillering of rice. The irrigation theory and technique for sun-drying rice fields at the late stage of rice tillering and drying the fields immediately at ripening were gradually perfected in the 1960s. This saved a lot of irrigation water (Liang 1983; Shen 1985). In the 1970s, double- or triple-cropping rice spread throughout China to increase the supply of the staple food. Some drylands were changed to rice fields. Subsequently, the water shortage became more serious in many regions. Moreover, the temperature was too low in spring and autumn to grow double-cropped rice in many places. Experiments were conducted aiming at utilizing the rainfall and regulating the thermal capacity of rice fields through irrigation and drainage measures. The “shallow with frequent irrigation” and “shallow irrigation and deep storage” techniques were recommended (Shen 1985; Zhu and Gao 1987).

The systematic research on WSI techniques for rice in China started around 1985 (Fang 1989; Zhu and Gao 1987). The impetus came from different aspects. Along with the great economic reform in China at the beginning of the 1980s, electricity and food were in short supply and water demand from industrial, domestic and hydropower generation users increased sharply.

In east China, the shortage in electricity was the most important factor to limit the economic development. Here, most electric pumps supplied water for rice culture. The consumption of energy by agriculture has a lower economic return but the central government should ensure the supply of energy for food security. Therefore, local governments sponsored irrigation and agricultural scientists to study WSI for saving energy.

The main task for agricultural development in the central part of China was to improve the low yield from rice fields with subsurface waterlogging and cold groundwater. The characteristics of these fields are poor soil aeration and low temperatures of water and soil. In the fields, the fertilizers are transformed slowly to efficient nutrients, and rice assimilates the nutrients with difficulty (Liang 1983). Combined with the engineering measures, such as building surface or subsurface drainage systems and rehabilitating irrigation systems to control the irrigation water diversion, and following successful experiments, the alternate wetting and drying (AWD) irrigation technique spread (Liu 1998; Zhu and Gao 1987).

In south China, developing cash crops in hilly areas was restricted because of the water shortage. WSI techniques for rice were researched and applied to save water for cash crops. In other regions, the water shortage was more serious. More research on WSI techniques was undertaken to reduce irrigation water use for rice (Li 1999; Liu 1998; Peng et al. 1997; Xu et al. 1990). As a result, a similar theory on WSI for rice was found from different motives; i.e., higher rice yields could be obtained without the need for continuously flooded irrigation, and the water content in the root zone of rice could be as low as 70 percent to 80 percent of saturated moisture (Li 1999; Li and Cui 1996; Li et al. *Experiment study,* 1994; Mao 1997; Peng et al. 1997; Wang 1992; Xu et al. 1990; Zhang et al. 1994).

In the beginning of the 1990s, the AWD irrigation practice for rice was promoted in most rice-growing areas of China. During the demonstration and implementation, the terms “shallow-wet-exposure,” “intermittent submerged irrigation,” and “thin-shallow-wet-exposure” were used in different Provinces of China for farmers to understand and remember the techniques easily. Remarkable benefits from real water saving were reported (Feng 1998; Li 1999; Liu and He 1996; Liu 1998; Mao 1997; Peng et al. 1997). Meanwhile, the central government attached great importance to agriculture and water saving, and some scientists engaged in WSI research were cited and awarded for their work. This encouraged more people to do research on WSI and more organizations to sponsor the WSI research.

The AWD irrigation technique for rice just concerned the on-farm level water saving but not the requirements for irrigation conveyance and labor input. In practice, some problems resulted from low irrigation duty and frequent irrigation applications. Because of this, the intermittent submerged irrigation (ISI) method for rice fields is promoted nowadays. This practice is the AWD, which allows rice fields to reach a very dry condition prior to receipt of further water and to store more water after rainfall. So the utilization of rainfall is facilitated, irrigation water management of the canal system is eased, irrigation events are reduced greatly and percolation and seepage losses from rice fields are reduced (Feng 1998; Li 1999; Li and He 1999; Wu 1998; Wu et al. 1995).

Theoretic Research of WSI for Rice

Policies and Conditions for the Research

The central government recognized the severity of the water shortage very early, and national conferences on WSI have been held quite often in recent years. Water saving has been one of the basic national policies and has been generally perceived to be a “revolutionary measure” for sustainable increases in the economy and agriculture in China (Feng 1998; Liu and He 1996; Zhang 1997). Both the Scientific and Technical Ministry and local governments were required to increase funds for sponsoring the research enthusiastically and organizing the application of advanced experiences energetically (Zhao 1997).

There are more than 500 stations for irrigation experiments in China and experimental research on WSI for rice has been the main work at more than 150 stations for many years. These stations do irrigation experiments with lysimeters and controlled plots collaborating with professional institutes or universities and then demonstrate the WSI practices to farmers at the field level.

Theoretic Research

The systematic research on WSI was started for drought-tolerant rice in Hubei and Anhui Provinces at the beginning of the 1980s (Fang 1989; Li 1999). The results could not bring to light the relationships between water input and the rice yield but indicated that a slight water stress did not reduce rice yields (Fang 1989; Li 1999; Zhu and Gao 1987). Since the 1990s, some advanced research projects have been sponsored by the Natural Scientific Foundation Committee of China and other organizations, and systematic achievements have been obtained. The main issues that have been addressed are as follows:

- *Impacts of WSI on the physiological mechanism of rice*. More attention was paid to comparing and analyzing the rice physiological indexes such as the root parameters, tiller, leaf area index (LAI), stomata behavior and yields with different water supplies (Fang 1989; Fang et al. 1996; Li 1999; Zhang et al. 1994).

- *Changing of the environmental conditions in rice fields with WSI*. The changes of soil aeration, temperatures, diseases, insect pests, cultures and population of weeds in rice fields with different water regimes were compared and analyzed (Li et al. *Experiment study,* 1994; Mao 1993; Zhang et al. 1994).

- *Rice evapotranspiration (ET) with different water supplies*. All experiment stations in rice-growing areas have been asked to do research on the changing patterns, influencing factors, estimation and forecasting of rice ET to meet the requirements for planning and design of irrigation projects, planning of developing water resources of basins, irrigation scheduling and irrigation water allocation.

- *Irrigation regimes for effective water and nutrient use by rice*. The field contrast experiments for approaching the optimum irrigation regime for effective water use by rice were started in many stations in the beginning of the 1980s (Li et al. *Experiment study,* 1994; Liu 1998; Peng et al. 1997; Wang 1992; Wu et al. 1995; Xu et al. 1990; Zhu and Gao 1987). From 1996, the research was combined with effective nitrogen (N), phosphorus (P) and potassium (K) use by rice, and the assimilation, transportation and escape of N, P and K in rice fields with different water regimes were addressed (Lu et al. 1997; Lu et al. 2000; Wu 1998).

- *Rice water-production functions (WPF) and the application*. Based on experimental data, WPF for different rice varieties (early, middle or late rice) and in different regions have been recommended, and the regularity of the variation of water sensitivity parameters in various models has been analyzed (Cui et al. 1998; Li 1999; Mao and Cui 1998). In some regions, the optimum irrigation regimes for rice fields were obtained in line with the WPF (Cui et al. 1995; Cui et al. 1997; Li 1999).

Findings

- Normally, it is necessary to keep shallow ponded water until the middle stage of rice tillering. Afterwards, AWD irrigation does not give negative impacts on the growth of rice if the water content in the root zone is not lower than 80 percent of the saturated moisture (Li 1999; Li et al. *Experiment study,* 1994; Zhang et al. 1994). Sometimes, there is an advantage in getting bumper crops with the well-developed rice roots resulting from the oxidized conditions and bigger area of upper rice leaves resulting, in turn, from an “overshoot” of growth after slight water stress in a short period (Fang et al. 1996; Li 1999; Lu et al. 1997; Wang 1992; Zhang et al. 1994).

- Some weeds grew well under continuously submerged conditions but others emerged when there was no deep-ponded water layer. Neither continuously flooding nor long-time drying controlled weeds effectively. The alternate flooding and drying was good for weed control in rice fields.

- ET is mainly affected by climatic factors and, to some extent, is controlled by physiological functions of rice under submerged conditions. However, the physiological characters of rice are considerably different before, during and after water stress. ET is lower than normal treatments during the period of stress and for several days following re-watering because of both a lower LAI and a leaf stomatal resistance, but ET will surpass that of continuous submerged treatments in later periods because of the “overshoot” (Li and Cui 1996). Therefore, the contribution of rice plant to ET should be considered separately before, during and after water stress when estimating ET with the Penman-Monteith method. The effects of soil factor should be considered according to the soil-moisture content of rice fields as well (Li 1999; Li and Cui 1996; Li et al. *Patterns and affected factors* 1994; Li et al. 1995).

- The AWD increases available nitrogen and phosphorus remarkably. Especially, the nitrogen nutrient could be transferred to the rice plant-growth center under AWD conditions in light of the experiments, and the nitrogen content in an ear of rice with AWD practice was always much higher than that under continuously flooded conditions. On the other hand, the uptake efficiency of potassium by rice might be lower with AWD practice (Lu et al. 1997; Lu et al. 2000; Wu 1998).

- The Jensen model is the applicable model of WPF for rice in China (Mao and Cui 1998). For early rice and middle rice, the water sensitivity index in the Jensen model always reaches the highest value at the growth stage of heading and flowering. For late rice, it reaches the highest value at the growth stage of elongating and booting (Cui et al. 1998; Li 1999; Mao and Cui 1998).

- In general, serious water stress during the tillering stage leads to the reduction of the panicle number but results in an increase of filled grain number and the weight of thousand-grain. Both the panicle number and filled grain number are slightly decreased if water is short in the booting stage. The filled grain number will be evidently reduced if rice suffers serious drought during the heading and flowering stage. The degree of drought stage when rice suffers water stress and the duration all give expression to the rice yields, and the reduction of rice yield is most sensitive to the duration of the drought (Li 1999; Zhang et al. 1994).

Application of WSI Techniques

Policies

A series of policies has been drawn up, such as Water Law, Water Resources Protection Law, Water Charge Rules, etc. "Pursuing WSI and taking shape a water-saving society" is one of the national basic policies, which is the highest law in China. Water shortage is not only the key problem in economic development but also one of the most important political topics. Professional or regional conferences on WSI are held often. The central government asked that WSI should be promoted as a revolutionary approach and the governor of province or county should be responsible for building advanced agriculture. The achievement in developing the sustainable agriculture and lightening the burden on farmers is one of the most important indexes for checking on cadres on different levels, which spurs leaders on to bring into line the benefits of farmer, irrigation agency, region and the state.

From 1980, irrigation agencies were asked to support themselves financially except for the infrastructure construction. The reform of water charge provided a basis for irrigation agencies to change the water allocation policy. Under the macroscopic control of the state, the provincial governments issued the water charge policies about rates and collection. The water rates for agriculture, industry, municipal and hydropower are quite different, and of these, the water rate for irrigation is the lowest. But irrigation claims first priority if water is lacking. Irrigation water is charged mainly based on the volume of water used.

Spreading of WSI Techniques

According to the Irrigation Experiment Rule in China, the research on WSI techniques should be carried out with more than 3 years of plot experiments, and then be demonstrated in typical fields. What has been applied successfully in trial rice fields will be spread in orderly fashion. First, policies for water saving and advantages for adopting WSI practice are propagandized widely via various media. Second, training courses and guidelines are given to heads of farmer groups and some farmers. Third, technicians direct farmers in rice fields. In addition, in some regions, such as the Guangxi Province, the responsibility records for spreading WSI techniques are signed level by level from province to village.

Incentives

After the reform of water charge, irrigation agencies have to improve management of irrigation water in order to transfer more water from agriculture to other purposes and increase the benefits from the same water quantity. They have incentive to do research on WSI techniques and help farmers to adopt WSI practices enthusiastically. Although farmers would pay less water fee if they use less water, this is often more than compensated by higher paying cities and industries. In humid areas, farmers believe WSI practices lead to higher rice yields because the aeration in rice fields is improved. In some regions, because the irrigation interval is longer and irrigation events are less, farmers are able to work a longer time in cities when they adopt the AWD technique for rice. Another reason for farmers to welcome WSI is that the application of WSI practices need a sound irrigation system and reliable water supply. Therefore, in areas practicing WSI, the central government and irrigation agencies will pay more attention to the modernization of irrigation systems.

Improvement of Irrigation Systems

On the one hand, there is a huge budget from the central government for the modernization of irrigation systems aiming at increasing water efficiency or water productivity and, on the other, irrigation agencies have the financial capacity for perfecting the irrigation system, especially the distribution systems, and strengthening the maintenance and operation after the reform of water charge. This is because they are able to transfer the savings from irrigation to more beneficial sectors. The “melons-on-the vine” irrigation system with functions of “big, medium, small; storing, diversion and lifting” is built, and the reliability of irrigation water supply is improved.

Combined with other measures, such as regulation of the cropping pattern, recycling of water, canal lining and introduction of small tanks to catch return flows, good results from the application of WSI techniques have been achieved. WSI techniques have been applied in more than 3.5 million hectares of rice fields, and the impacts of WSI on economic and agricultural development are profound (Feng 1998; Li et al. 1998; Liu and He 1996; Zhang 1997; Zhao 1997). Many reports in China (Li 1999; Liu and He 1996; Peng et al. 1997; Wu 1998) claim that the WSI techniques could increase on-farm water productivity by 20 percent to 35 percent compared with the traditional irrigation practices.

Conclusion

Gigantic efforts have been made for the research and practice of WSI for rice, and considerable benefit has been obtained in China. The WSI has struck root in the hearts of the people, which leads to a sound environment for both research and practice of the WSI techniques. However, there remain many scientific issues that have not been addressed. Research on efficient water use at system level or basin level is lacking. Real water savings at the system level cannot be quantified, and there is no systematic theory for modernization of irrigation systems. The field experiment is the weak link in China. Funds for experiments and demonstrations are always short, and the number of scientific research workers engaged in the fieldwork are not enough. In addition, the application of WSI techniques in some regions is still very difficult because of both physical and institutional problems. But farmers should never bear the responsibility for non-adoption of the WSI practices. Some irrigation agencies are not able to transfer water to domestic and industrial water users and are thus not interested in the application of WSI techniques. Therefore, scientific, policy and institutional issues related to the WSI practices are all important and increasing attention should be paid to them in the coming years. The cooperation of water and agricultural scientists is needed in the research and practice of WSI techniques. Technical support from international institutions is necessary.

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Chapter 2

Analysis of Changes in Water Allocations and Crop Production in the Zhanghe Irrigation System and District, 1966–1998

L. Hong, Y. H. Li, L. Deng, C. D. Chen, D. Dawe and R. Barker

Introduction

The Zhanghe Irrigation District (ZID) is situated in the middle part of China north of the Changjiang (Yangtze) river.[1] The area of the Zhanghe basin is 7,740 km^2 including a catchment area of 2,200 km^2. The Zhanghe Irrigation System (ZIS) accounts for most of the irrigated area within ZID. It is one of the typical large-size irrigation systems in China. Its designed irrigation area is about 160,000 hectares. The Zhanghe reservoir, built between 1958 and 1966 on a tributary of the Changjiang river, supplies most of the irrigation water to ZIS. The reservoir was designed for multipurpose uses of irrigation, flood control, domestic water supply, industrial use and power generation.

This paper describes and analyzes the changes in water allocation and crop production in ZIS and ZID over the 33-year period 1966–1998. From the late 1970s to the late 1990s, water allocated to irrigation from the Zhanghe reservoir dropped from 600 million cubic meters (mcm) to about 200 mcm (figure 1). The water allocated for other uses (municipal, industry and hydropower) has increased steadily. By the end of the 1990s, irrigated area and production had declined considerably but by much less than the decline in deliveries of irrigation water. In analyzing these changes, we identify those factors that seem to have contributed to the increase in water productivity.

This paper is divided into seven sections. The first section discusses the sources of data and the rationale for dividing and averaging the data across three separate time periods. The second section describes available water resources in the main reservoir and the change over time in water allocation among alternative uses. The third section describes trend over time in water releases from the main reservoir and from other ZIS sources. The next two sections describe the changes in area irrigated and crop production over time. The sixth section discusses the factors that may have contributed to increases in crop production and water productivity over time and identifies the most probable sources of growth in water productivity. The final section presents the conclusions.

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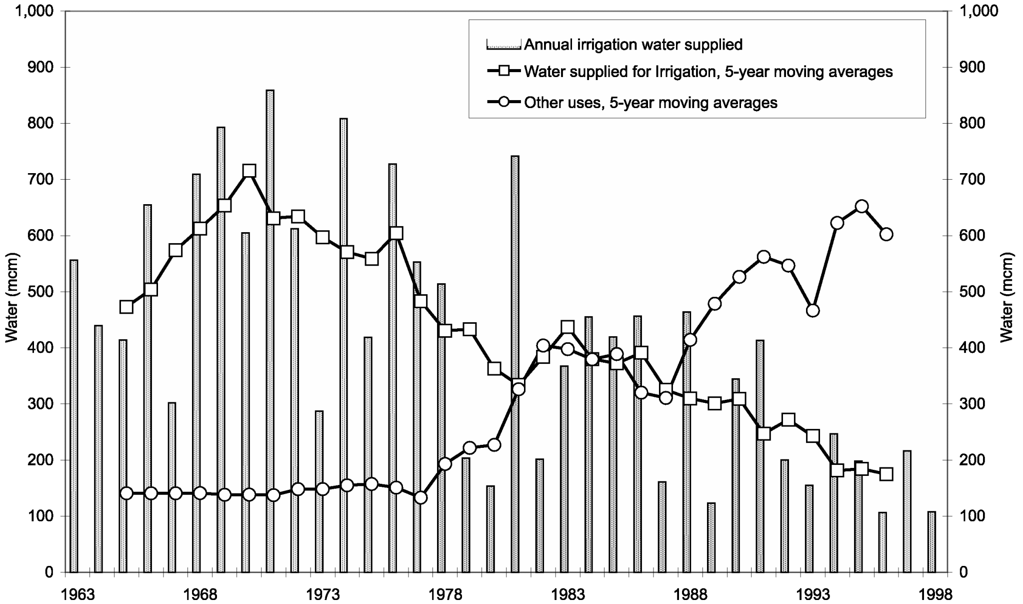
[1]ZID is an administrative unit consisting of all or parts of several county and city jurisdictions. The water used by ZID comes principally from the main reservoir although smaller reservoirs and other sources such as groundwater also supplement this water.

Figure 1. Annual water allocations for irrigation and other uses, ZIS, 1965–1998.



Analysis of Data by Trend and Time Period

The time series on which this report is based was compiled by ZIS for the period 1966 to 1998. The full data are presented in a series of four tables in the annex to this paper. The figures in the text show the trends over time. In the text tables, however, mean values are shown for three separate time periods, 1966–78, 1979–88 and 1989–98. This division was made to reflect the very sharp changes that occurred at the end of the first and second time periods.

Following the end of the Cultural Revolution in the late 1970s, significant reforms took place that affected both irrigation and agricultural production. Volumetric pricing was introduced. New pumping stations were built. Medium- and small-size reservoirs were restored or expanded. Introduction of improved varieties and increased use of chemical fertilizers led to a sharp increase in rice yields.

The end of the 1980s saw further changes. The installation of two new hydropower plants greatly increased the hydropower capacity. Industrial and domestic demand also rose, resulting in a further decline in water available for irrigation. The pressure to save water led to an expansion of the alternate wetting and drying (AWD) irrigation techniques at the farm level and to other water-saving practices such as canal lining. The introduction of hybrid rice gave a further boost to rice yields.

Regulation and Allocation of Water among Alternative Uses in the Zhanghe Reservoir

In ZIS, most of the irrigation water comes from the Zhanghe reservoir but with substantial supplies from medium- and small-size reservoirs (table 1) and supplemented by a pumping station. Thus, a large irrigation network including storing, diverting and withdrawing water has been established.

Table 1. Water supplied for irrigation in ZIS, by source.

Million mcm x 100				
Period	Main reservoir	Small reservoirs	Other sources	Total
1966–78	6.03	1.50	0.96	8.50
1979–88	3.63	2.47	1.65	7.74
1989–98	2.11	1.17	0.81	4.10

The water available for irrigation includes rainfall, water from the main and small reservoirs, river water and groundwater. The annual rainfall is 960 mm with a standard deviation of approximately 20 percent. Also, in more recent years, there have been significant releases of water for flood control. The flood year 1996 provides a clear example. The rainfall (1,354 mm) and inflow (16.4 x $10^8 m^3$) were abnormally high. Water released for flood control (8.2 x $10^8 m^3$) was the highest on record. When water released for flood control is adjusted, the available supply of water from the Zhanghe reservoir does not appear to have changed significantly over time.

Why water releases for flood control have increased over time is not clear. However, if in earlier years surplus water was released into the irrigation system this would help explain why water productivity was so low in the first period. There are large year-to-year fluctuations in rainfall, which affect the annual releases for irrigation (figure 1). When rainfall is low and the irrigation system needs more water for irrigation, the water yield from the catchment is small. When the irrigation system needs less water, the water yield from the catchment is usually large. Varying water storage across years deals with this problem.

Zhanghe is a multipurpose reservoir. While the primary purpose is irrigation, other uses include flood control, hydropower, municipal and industrial water supply, navigation and aquatic culture. The tasks of regulation are based on planning, design and experience. The objectives of water supply are subordinate to flood control and the prerequisite of reservoir safety. As much water as possible is stored to meet water demand for all users, but irrigation has first priority. In years of extreme shortage, such as in 2000, industrial and municipal demands had first priority followed by agriculture. Thus, water for hydropower is reduced.

In the 1966–78 period, the main water use was irrigation but water was not managed well. The standard of flood control was low. There was excess water at the upper end of the canal but, often, farmers at the lower end did not receive water. In the period 1979–88, there were substantial improvements in regulation and management, and volumetric pricing of water was initiated. In the most recent period, 1989–98, new management tools and information technologies were tested and implemented. These included multi-objective optimization modeling, real-time information feedback for forecasting weather and inflow into the reservoir, and remote sensing. Reservoir regulation and flood control were successfully linked with weather forecasting. In summary, improvements in regulation and management have improved the capacity of the Zhanghe reservoir in flood control and in satisfying demands for water among alternative users.

Over the past three decades, with the increase in population and industry, the water demand from city, industry and power generation has increased (figure 1). Jingmen city, a few kilometers from the Zhanghe main reservoir, is a new industrial city with a population of about one million. Jingmen has developed quickly in recent years. The central, provincial, and prefectural governments have established a number of factories in the city. Major industries include oil, chemicals, textiles and leather. In addition to Jingmen city, other smaller cities and towns have developed rapidly, placing a growing demand on water for industrial and municipal uses. The Zhanghe main reservoir supplies water to Jingmen city, while groundwater or medium and small reservoirs supply domestic water for smaller cities and towns.

However, the largest increase in water allocation has been for hydropower, followed by industrial and municipal uses (table 2). The Zhanghe main reservoir was designed with one hydropower plant of 2 x 800 kW capacity utilizing, on average, a water supply of 0.84 x 10^8 m^3. In contrast to most irrigation systems, the water flowing through the generators cannot be diverted back to irrigation. In 1989 and 1995, two new hydropower sets of 1 x 800 kW and 2 x 1,600 kW were installed. The water allocated to hydropower in the 1989–98 period exceeded the water allocated to irrigation—2.5 v 2.1 10^8 m^3 per annum (table 2). As a result of the growth in demand by hydropower and other sectors, the amount of water from the Zhanghe main reservoir allocated to irrigation in the past decade has declined to one third of its 1966–78 level (6.0 to 2.1 x 10^8 m^3).

Table 2. Water inflow and releases from the Zhanghe reservoir.

Period	Average Water Uses (mcm X 100)							Rainfall (mm)
	Irrigation	Industrial	Municipal	Hydroelectric	Flood control	Evaporation	Inflow	
1966–78	6.03	0.17	-	0.25	0.15	1.24	69,387	952
1979–88	3.62	0.37	-	0.53	2.27	1.19	75,275	967
1989–98	2.12	0.48	0.15	2.51	2.83	1.23	90,273	967

1975–78 Average for industrial water use.
1973–78 Average for hydroelectric water use.

Changes in Irrigation Water Supplies in ZIS

Figure 2 compares the trend in sources of irrigation water supply over time for ZIS. In the 1960s and 70s, the main reservoir supplied three quarters of the water for irrigation, but now it supplies only half. The water supply for irrigation by ZIS has dropped sharply since the mid-1980s.

Figure 2. Water use for irrigation by ZIS from different sources, 1966–1998.

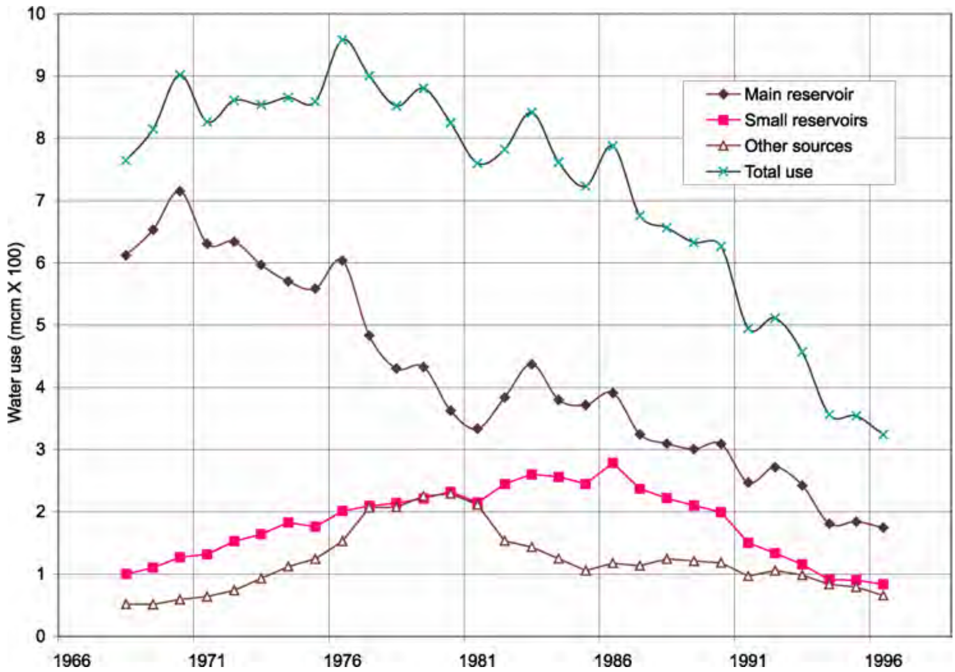


Table 1 shows the water supplied for irrigation in ZIS over three time periods. Despite the sharp drop in the water supply from the reservoir in the 1979–88 period, the total water supply for ZIS declined less than half. This is because in the 1980s a number of medium-size reservoirs and ponds were restored or constructed to increase the water-storing capacity. This evened out farm-level water availability from year to year and provided greater water control during the cropping season, facilitating water saving through AWD management of water in rice fields. In the 1990s, however, the ZIS irrigation water supply from other sources declined. This seems to be because many of the medium- and small-size reservoirs were required to support themselves and were technically no longer a part of ZIS.

Changes in Crop Area Irrigated in ZID and by ZIS

Table 3 shows the crop area irrigated in ZID and by ZIS for three time periods. Most of the irrigation is for rice. Figure 3 compares the trend in rice area irrigated by ZIS and rice area under irrigation in ZID. In the 1966–78 period, the area irrigated in ZID and by ZIS approximated the command area. However, by the end of the 1990s, rice area irrigated had declined substantially compared to the end of the previous decade. In the 1995–98 period, rice irrigated area declined by 36 percent in ZIS and by 25 percent in ZID over the 1985–88 period. While this decline is relatively large, it is much less than the 61 percent decline in irrigation water supplied by ZIS over the same period.

Table 3. Command area and area irrigated by ZID and in ZIS (1,000-ha units).

Period	Command area		Area irrigated in ZID		Area irrigated by ZIS		Uplands
	Total	Rice	Total	Rice	Total	Rice	
1966–78	150	138	143	138	134	130	19
1979–88	156	142	140	134	103	100	35
1989–98	147	131	133	118	82	77	63

The smaller decline in irrigated area in ZID as compared to ZIS appears to be due to the development of new sources of water that are not under ZIS management. For example, tanks not under ZIS management capture the drainage water from ZIS. As the downward trend in irrigated area in both ZIS and ZID continued in the late 1990s farmers have increased the area planted to upland crops (table 3).

Change in Rice Crop Production and Land and Water Productivity in ZID

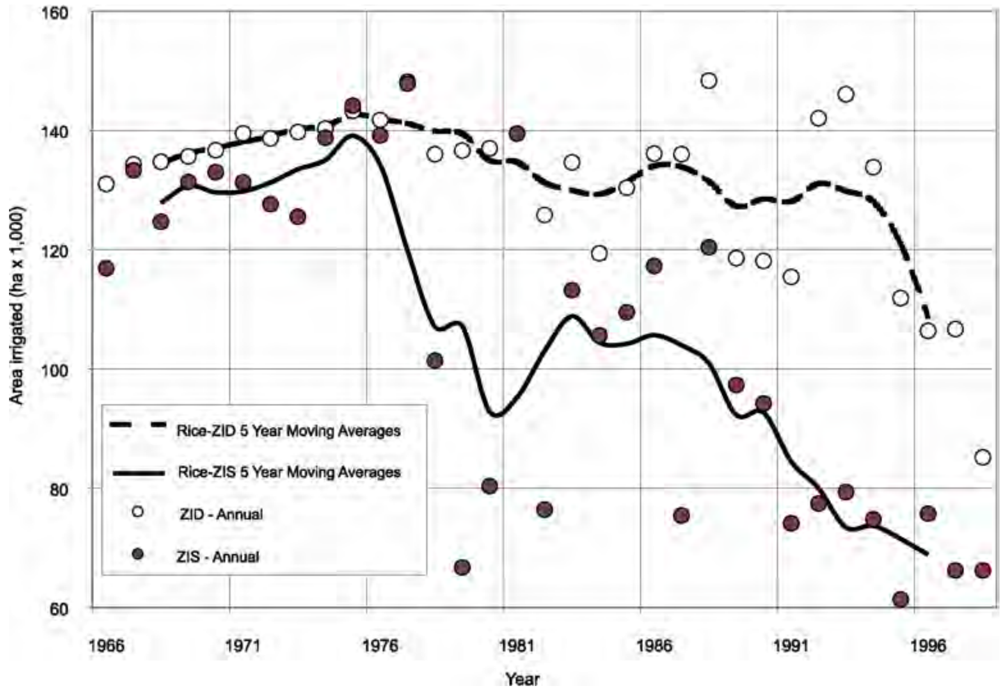
What impact does the reduced allocation of water for irrigation have on crop production, and on land and water productivity? The reported rice-grain production, planted area, and rice yield per hectare for ZID are shown in table 4. Rice production rose sharply in the period 1979–88 compared to the previous period despite a decline of 13 percent in planted area. This is because rice yields rose sharply due to the spread of modern varieties and increased use of chemical fertilizers following the change in agricultural policies at the end of the Cultural Revolution. Over the three time periods the yield per hectare of rice doubled. When rice irrigated area began to decline substantially by the second half of the 1990s, rice production followed suit as yield growth had slowed to almost nothing. Comparing 1995–98 with 1985–88, rice area planted declined 27 percent while average yields rose by just 4 percent. The net effect was a 24 percent fall in rice production. To some extent, this was compensated for by increased production of upland crops.

Table 4. Changes in rice irrigated area, planted area, production and yield in ZID.

	Irrigated area ha x 1,000	Planted area ha x 1,000	Rice production MT x 1,000	Rice yield t/ha	Water supplied Million mcm x 100	Yield* kg/m^3 (irrigation)
1966–78	138	173	698	4.04	8.50	0.82
1979–88	134	151	1,015	6.72	7.74	1.31
1989–98	118	122	952	7.80	4.10	2.32

Note: MT=Metric tons.
***** Upper limit, see text for discussion.

Figure 3. Rice area irrigated by ZIS and ZID, 1966–1998.



There are no data of ZID water supply for irrigation. However, if we assume that the main supply of water to areas in ZID not served by ZIS is the ZIS drainage water, then we can estimate the change in water productivity. This assumption seems reasonable since in the period 1966–78 the area irrigated by ZIS and ZID was almost identical. However, to the degree that this assumption does not hold, the water productivity values shown in table 4 represent an overestimate. For example, if it were assumed, as stated earlier, that the reservoirs formerly under ZIS control were still supplying water to ZID, then the water productivity in the third period would be approximately the same as in the second.

Factors Contributing to the Increase in Crop Production and Water Productivity

Long-term trends in water allocation across sectors and in yield per hectare and per cubic meter of irrigation water supplied show that there have been water savings and a considerable increase in water productivity over time. Despite the decline in water for irrigation from the reservoir (figure 1) and in the area irrigated in ZID, crop production has been sustained.

Several factors may have contributed to sustained rice production including: i) economic and institutional reforms initiated in 1978, ii) a shift in cropping pattern from two to one crop of rice, iii) on-farm and system WSI practices (e.g., AWD irrigation of rice fields), iv) volumetric pricing of water, which may have encouraged AWD irrigation, v) development of alternate sources of water such as small reservoirs and groundwater, and vi) recapture and reuse of return flows through the network of reservoirs. Of course, the various changes that occurred are not independent of each other but we are attempting to identify more precisely the contribution of each of these factors.

Table 5 shows that the trends in yield per hectare of rice for ZID, Hubei Province, and all China are remarkably similar. It seems reasonable to assume that the increase in yield per hectare in ZID explains more than half of the increase in water productivity. But a substantial amount of the gain in water productivity remains to be explained by other factors.

Table 5. Annual percentage increase in rice yields for China, Hubei and ZID.

Period	China	Hubei	ZID
1966–78 to 1979–88	3.9	4.2	5.2
1979–88 to 1989–98	2.0	2.6	1.7
1966–78 to 1989–98	3.0	3.5	3.5

AWD irrigation may be one of the reasons behind the increase in water productivity in ZIS over time. Chapter 5 of this publication shows that many farmers have adopted some form of AWD irrigation while chapters 4 and 5 show that adoption of AWD irrigation has no effect on yields. Coupled with the reduced water use in AWD irrigation, this leads to an increase in water productivity, at least at the farm scale. However, it has proved difficult to quantify the system-level effects of increased water productivity at the farm scale.

In the future, we would like to see whether water-saving technologies used successfully in China can be utilized in other rice-growing areas of the world. We feel that WSI practices such as AWD irrigation and recapture of return flows are suitable for monsoonal areas where there is considerable outflow that could be saved and put to productive use. In the more arid regions, especially those where water resources are already committed to various uses, the scope for water saving by AWD irrigation and related techniques may be more limited.

Conclusions

ZIS was originally designed as a multipurpose reservoir but water was supplied initially only for irrigation. Gradually, the supply and management of water for other purposes have grown in importance. These include flood control, hydropower, and municipal and industrial water needs. The reservoir also serves environmental needs, tourism, aquatic culture and navigation.

In this paper, we have examined the trends in water allocation among sectors, in area irrigated, and in crop production and productivity. As water demand has grown for purposes other than irrigation, the water supplied to irrigation has fallen sharply. To maintain crop production, several water-saving practices have been adopted. While yield per hectare has doubled from the 1960s to the 1990s, yield per cubic meter of water supplied appears to have tripled.

There are a number of factors that may have contributed to the increase in water productivity, including AWD irrigation, improved system management, volumetric pricing, development of new water sources that reduce uncertainty surrounding water availability during key crop-growth stages and improved reuse of drainage water. A major objective of future research will be to identify those practices that could be successfully extended to other regions, both inside and outside China.

Annex table 1 contains data for the Zhanghe reservoir for the period 1966–1998.

Zhanghe Irrigation Reservoir

Annual inflow, water releases for alternative uses and other losses
Cubic meters x 10,000

Year	Water uses					Evaporation	Inflow	Rainfall (mm)
	Irrigation	Industrial	Domestic	Hydro-electric	Flood Releases			
1966–78	60,325	1,667		2,459	1,473	12,434	69,387	952
1979–88	36,245	3,659	931	5,277	22,716	11,943	75,275	967
1989–98	21,165	4,826	1,487	25,128	28,340	12,280	90,273	967
1966	65,441				1,473	12,448	44,462	772
1967	30,198					10,991	94,389	1,192
1968	70,916					15,444	109,060	1,138
1969	79,281					15,907	77,388	1,014
1970	60,455					14,401	62,256	949
1971	85,928					12,391	91,919	1,064
1972	61,207					11,195	29,302	646
1973	28,666			4,720		10,146	123,632	1,214
1974	80,859			6,508		14,766	44,053	819
1975	41,854	1,375		779		12,242	99,250	1,173
1976	72,726	2,218		710		12,796	31,110	724
1977	55,314	1,559		120		10,746	59,939	865
1978	51,378	1,517		1,915		8,165	35,275	801
1979	20,371	2,672		982		8,704	92,729	1,156
1980	15,364	2,832		2,969	24,576	14,093	126,234	1,181
1981	74,159	2,783		1,250	10,275	15,791	39,577	740
1982	20,164	3,690		818		10,522	87,674	982
1983	36,764	2,763		2,826	43,632	12,017	118,802	1,223
1984	45,546	3,316		7,699	27,368	12,787	76,517	1,005
1985	41,966	4,155		17,457	7,727	12,058	57,964	931
1986	45,656	4,511		5,247		11,117	28,932	772
1987	16,067	5,070		4,227		10,504	81,319	994
1988	46,391	4,797	931	9,298		11,837	43,003	687
1989	12,297	4,126	1,236	19,546	11,905	9,592	121,400	1,239
1990	34,420	5,112	1,291	23,349	51,453	12,033	94,558	1,049
1991	41,362	5,138	1,474	19,315	14,191	12,842	90,122	936
1992	20,022	4,947	1,279	19,243	2,793	13,383	65,286	878
1993	15,489	4,553	1,441	21,857		11,870	81,417	811
1994	24,656	4,137	1,482	15,838		12,324	48,573	763
1995	19,768	4,566	1,681	28,219		12,621	74,878	871
1996	10,663	5,027	1,623	25,934	81,525	12,610	164,171	1,354
1997	21,646	5,556	1,677	29,685	16,685	13,364	63,526	783
1998	11,329	5,095	1,689	48,293	19,830	12,163	98,799	988

Note: Data are reported on the annual releases of water for alternative uses (irrigation, industry, domestic, hydropower). There are also data on inflow, loss due to evaporation, releases for flood control and on annual rainfall.

Annex table 2 shows the amount of water released for irrigation in ZIS for the period 1966–1998.

Zhanghe Irrigation District

Year	Annual water sources for irrigation in ZIS Million cubic meters x 100			
	Water uses			
	Main reservoir	Small reservoirs	Other sources	Total sources
1966–78	6.03	1.50	0.96	8.50
1979–88	3.63	2.47	1.65	7.74
1989–98	2.11	1.17	0.81	4.10
1966	6.54	0.79	0.60	7.93
1967	3.02	0.97	0.52	4.51
1968	7.09	1.13	0.57	8.79
1969	7.92	1.04	0.46	9.42
1970	6.04	1.08	0.45	7.57
1971	8.59	1.29	0.57	10.45
1972	6.12	1.82	0.92	8.86
1973	2.87	1.36	0.80	5.03
1974	8.08	2.09	0.97	11.14
1975	4.18	1.65	1.39	7.22
1976	7.27	2.23	1.53	11.03
1977	5.53	1.47	1.54	8.54
1978	5.14	2.63	2.21	9.98
1979	2.04	2.51	3.69	8.24
1980	1.54	1.86	1.42	4.82
1981	7.41	2.61	2.41	12.43
1982	2.02	2.03	1.73	5.78
1983	3.68	1.72	1.34	6.74
1984	4.55	4.03	0.77	9.35
1985	4.20	2.64	0.93	7.77
1986	4.56	2.41	1.48	8.45
1987	1.61	1.46	0.78	3.85
1988	4.64	3.40	1.93	9.97
1989	1.23	1.96	0.56	3.75
1990	3.44	1.87	1.48	6.79
1991	4.14	1.83	1.31	7.28
1992	2.00	0.92	0.63	3.55
1993	1.55	0.95	0.87	3.37
1994	2.46	1.12	1.01	4.59
1995	1.98	0.97	1.11	4.06
1996	1.07	0.60	0.57	2.24
1997	2.16	0.88	0.41	3.45
1998	1.07	0.61	0.19	1.87

*Note:*The release includes the water from the main reservoir, from smaller reservoirs and from other sources such as groundwater.

Annex table 3 shows the command area, the area irrigated in ZID (i.e., the irrigation district) and the area irrigated by ZIS (i.e., the irrigation system) for all crops including rice for the period 1966–1998.

Zhanghe Irrigation District

	Command area and area irrigated in ZID and by ZIS 1966–1998. ha X 1,000					
	Command area		Area irrigated in ZID		Area irrigated in ZIS	
Year	Total	Rice	Total	Rice	Total	Rice
1966–78	150	138	143	138	134	130
1979–88	156	142	140	134	103	100
1989–98	147	131	133	118	82	77
1966	141	130	136	131	121	117
1967	139	134	139	134	138	133
1968	146	135	139	135	127	125
1969	149	136	140	136	134	131
1970	143	137	141	137	135	133
1971	153	140	145	140	134	131
1972	154	141	145	139	132	128
1973	153	140	144	140	135	126
1974	152	139	143	140	140	139
1975	154	141	147	143	146	144
1976	154	140	145	142	141	139
1977	155	141	149	148	149	148
1978	155	141	145	136	104	101
1979	154	140	141	137	70	67
1980	156	142	141	137	82	80
1981	155	142	144	139	144	139
1982	155	141	131	126	78	76
1983	151	140	137	135	121	113
1984	153	140	127	119	103	106
1985	162	142	142	130	117	110
1986	163	146	146	136	120	117
1987	161	143	136	136	75	75
1988	149	145	150	148	121	120
1989	148	142	119	119	99	97
1990	149	136	139	118	105	94
1991	165	133	153	115	90	74
1992	151	128	162	142	82	77
1993	142	133	148	146	80	79
1994	140	123	147	134	80	75
1995	149	134	136	112	77	61
1996	149	134	123	106	68	76
1997	149	134	112	107	76	66
1998	131	109	91	85	68	66

Conversion factor: 1mu = 0.0667 ha.

Note: Data for the ZID are obtained by ZIS from the counties and cities, a portion or all of which fall within the ZID.

Annex table 4 shows the ZID production, planted area, and yield per hectare for rice only. All of the rice is irrigated and most farmers grow only a single crop. Other grain crops are normally not irrigated.

Zhanghe Irrigation District

Area, production and unit yield of rice in ZID, 1966–1998

	Rice area planted	Rice production	Unit yield
Year	ha X 1,000	Mt X 1,000	kg/ha
1966–78	173	698	4,037
1979–88	149	1,001	6,719
1989–98	123	950	7,802
1966	154	637	4,125
1967	161	594	3,683
1968	166	638	3,840
1969	165	631	3,825
1970	170	677	3,990
1971	184	569	3,098
1972	168	491	2,918
1973	181	706	3,908
1974	184	719	3,900
1975	177	795	4,500
1976	180	887	4,920
1977	185	864	4,680
1978	169	863	5,100
1979	152	872	5,753
1980	150	806	5,355
1981	152	899	5,925
1982	150	913	6,068
1983	153	969	6,353
1984	152	1,046	6,885
1985	152	1,127	7,403
1986	139	1,112	8,025
1987	150	1,117	7,440
1988	144	1,147	7,988
1989	159	1,219	7,650
1990	167	1,237	7,395
1991	143	1,011	7,065
1992	122	1,029	8,445
1993	106	798	7,493
1994	101	797	7,905
1995	120	843	7,035
1996	103	819	7,988
1997	110	1,001	9,120
1998	94	746	7,920

Note: The information on production, area, and yield per hectare is obtained from various administrative offices in ZID and compiled by ZIS.

Chapter 3

Operation of the Zhanghe Irrigation System

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Abstract

This paper explores the water management of the Zhanghe Irrigation System (ZIS) tracing key decision points for water allocation and distribution. We outline the kinds of arrangements made at key points from the reservoir to farmers' fields, then consider the mechanism and the flow of money from farmers' fields to reservoir operators for the payment of services. We feel that delivery practices of canal water are very important to facilitate on-farm water-saving irrigation (WSI) practices. It is important to understand how water deliveries and payments are made in a large, complex irrigation system, so that lessons can be derived and applied elsewhere.

The ZIS, situated in the Hubei Province in central China, north of the Changjiang (Yangtze) river irrigates an area of about 160,000 hectares and is one of the most important bases of commodity grain in the Hubei Province. The main water supply is the Zhanghe reservoir. Apart from this reservoir there are tens of thousands of medium- and small-size reservoirs, small basins and pump stations in the Zhanghe Irrigation District (ZID) partly incorporated into the irrigation system but sometimes operating independently.

At the beginning of the irrigation season (end March, begin April) the Zhanghe Irrigation Administration Bureau makes a long-term forecast allocation plan for ZIS based on irrigated area, weather forecast and the condition of water sources (mainly storage in the main reservoir). The result is an overall scheme for water allocation and distribution. The water allocation to each main canal is based both on experience and on the requests coming from the water users in the command area. However, during the flooding season, the Hubei Provincial Government has the power to decide on the amount of water to be allocated to hydropower and flood-control release. As much water as possible is stored to meet the water demand for all sectors, but irrigation has first priority. In general, the Zhanghe reservoir has enough water to fulfill all requirements. About 42 percent of the total water release is allocated to agriculture and about 45 percent to hydropower while the rest is for industry and municipalities.

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The timing of the water releases from the reservoir depends on the weather situation. There are usually around three to five releases a year to any given branch canal. However in general, the third main canal receives water only twice a year, which is considerably less than what the fourth main canal receives. This difference is explained by the better local water sources (reservoirs and ponds) in the third main canal command area and light soils in some parts of the command area of the fourth main canal. The periods of water releases are almost the same every year.

While farmers do order water, many of the decisions about when to release water comes from higher levels in the canal-operations hierarchy. Thus it appears that the management of canal water has not only an element of farmer demand but also a strong element of a supply approach where reservoir operators make decisions based on available storage, rainfall and on an overall view of when crops need water. The ponds and small reservoirs located within the irrigated area allow farmers to get a much more flexible supply of water on demand. So the entire system functions as an on-demand system because of its in-built flexibility to store water close to the water users, which is a prerequisite for adopting WSI techniques like the AWD irrigation.

The Provincial Finance and Pricing Control Bureau determines the price per unit of water per sector. The price for agricultural use has more than doubled over the last decade. The Zhanghe Irrigation Administration Bureau charges the water fee on a volumetric basis. The water user groups and villages pay the water fee on a volumetric basis to the section office of the ZIS main canal. However, at the end of the season, the group and village heads convert this volumetric water fee into a water fee for the farmers based on area. The total volumetric fee paid to ZIS is divided by the total area of the group or village. Besides this water fee, which is related to the volume used by the group or village, farmers pay another type of flat water fee based on area, to be paid to the local government. People have to pay this water fee even if they do not use water.

Even though farmers pay a water fee per area they are quite aware of the link between the volume of water used and the price they have to pay for the water at the end of the season. For this reason, farmers minimize the amount of the Zhanghe irrigation water and catch rainfall to the maximum extent on their fields, use water from local sources that have no direct connection to ZIS and reuse drainage water, since this is for free.

Introduction

This paper explores the water management of ZIS, tracing key decision points for water allocation and distribution. We outline the kinds of arrangements made at key points from the reservoir to farmers' fields, then consider the mechanism and the flow of money from the farmers' fields to reservoir operators for the payment of services. We feel that the delivery practices of the canal water are very important to facilitate on-farm WSI practices. It is important to understand how water deliveries and payments are made in a large, complex irrigation system, so that lessons can be derived and applied elsewhere.

First, a short description of ZIS is presented after which we explore the water management of ZIS described as the water flows: from the reservoir down to the farmers, first considering farmer requirements. We also trace the flow of payments for water services, which is described as the money flows: from farmers up to the Zhanghe Irrigation Administration Bureau.

Zhanghe Irrigation District

The ZID is situated in the Hubei Province in central China, north of the Changjiang (Yangtze) river. The area of the Zhanghe basin is 7,740 km^2 including a catchment area of 2,200 km^2. The ZIS accounts for most of the irrigated area within the ZID. See text box 1 for features of ZID.

Text box 1. Features of ZID.

Crops. The main grain crops are rice and winter wheat. The upland crops are beans, sesame oil and sweet potatoes. Rice cultivation accounts for about 80 percent of the total area of which about 85 percent is planted by the middle-season rice (May to September).

Climate. The average annual air temperature is 16 °C, varying from a minimum temperature of –19 °C in January to a maximum near 41 °C in July. On average, there are 246–270 annual frost-free days.

Rainfall. The ZID is located in the subtropical zone and is affected by monsoonal rains. The average annual rainfall is 970 mm but it is unevenly distributed between years (the extreme values are 610 mm in 1966 and 1,330 mm in 1980) and over the year. On average, 82 percent of the annual rainfall occurs during the rice- and maize-growing season (April to October). The average rainfall decreases from south to north in ZIS.

Topography. The ZID slopes from an elevation of 120 m above sea level in the northwest to an elevation of 26 m in the southeast. About 80 percent of the irrigated area lies in the hilly region.

Soil. The soil textures of the irrigated area are mostly clay (57%) and loam (43%).

Zhanghe Reservoir

The Zhanghe reservoir was built between 1958 and 1966 on the Zhanghe river, a tributary of the Juzhanghe river, which flows into the Yangtze river. The reservoir was designed for multipurpose uses of irrigation, flood control, domestic water supply, industrial use, aquatic culture and power generation. The primary purpose is still irrigation. The reservoir consists of three main reservoirs connected by open channels. The main hydraulic structures are located along the southeast bank and include four main dams and one auxiliary dam (the highest about 67 m), three spillways and six diversion gates. See table 1 for reservoir features.

Table 1. Salient features of the Zhanghe reservoir.

Zhanghe reservoir		
Descriptor		Capacity (in billion m^3)
Catchment area	2,212 km^2	
Area covered by water	104 km^2	
Total storage capacity		2.035
Normal water level	123.50 m	1.783
Dead water levels	113.00 m	0.862
Average annual water yield		0.773

Zhanghe Irrigation System

The ZIS is one of the most important bases of commodity grain in the Hubei Province. It is one of the typical large-size irrigation systems in China and its total area is 5,540 km^2 of which about 160,000 hectares comprise the irrigated area. The ZIS incorporates nine classes of canals constituting one general main canal, five main canals and more than 13,000 branch canals with a total length of more than 7,000 kilometers and over 15,000 structures. Besides these, there are tens of thousands of medium- or small-size reservoirs, small basins and pump stations in the area partly incorporated into the system but sometimes operating independently. The Zhanghe reservoir supplies most of the ZIS irrigation water. The drainage system consists of natural streams and ditches.

Since the 1980s, a rehabilitation program has been carried out to improve the performance of ZIS. The strategies included popularization of WSI techniques like AWD irrigation, canal lining, volumetric charging of water, drainage water reuse and other management innovations. It is hypothesized that the popularization of the AWD technique, one of the strategies in the rehabilitation program, has enabled the reservoir to transfer water to other higher-valued uses without significant loss in crop production.

Water Resources of ZIS

Water resources of ZIS include reservoir water, precipitation, groundwater and river water (see text box 2 and table 2).

Table 2. Water sources of ZIS.

	Total water released for agriculture (%)		
	Zhanghe reservoir	Small reservoirs	Other sources
1966–1978	71	18	11
1979–1988	47	32	21
1989–1998	52	29	20

Text box 2. Water sources of the ZIS.

Reservoir water. The average annual water supply from the Zhanghe reservoir is about 0.500 billion m^3. There are about 86,000 small ponds and tanks. Besides these, more than 300 medium- and small-size reservoirs have been constructed with a total beneficial storage capacity of 0.819 billion m^3.

Precipitation. The average annual precipitation is 970 mm and the total average annual rainfall is 5.199 billion m^3. The observed average annual runoff is 2.15 billion m^3.

Groundwater. The groundwater resources are rich, distributed in a large area and are easy to exploit. No data are available about groundwater extraction.

River water. Along the Yangtze river, the Hanjiang river and the Changhu lake there are more than 430 pump stations with a total capacity 0.2 million kW. The annual water withdrawal from rivers is about 0.112 billion m^3.

Most of the data about the operation and payments for water services in ZIS were collected with the help of interviews with farmers and system operators at different levels. We also collected substantial data on long-term flow records of the Zhanghe reservoir and some main canals.

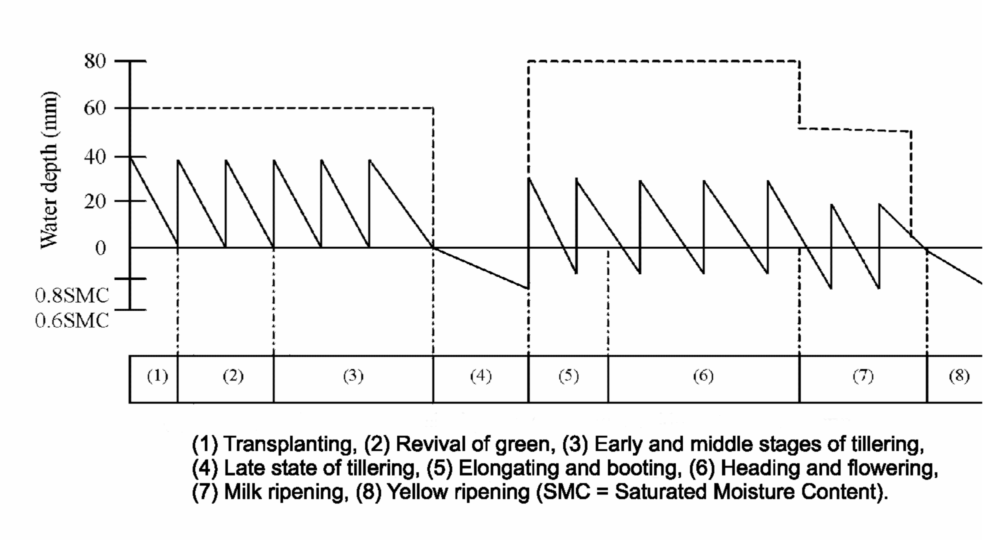
Operation

In this section we explore the management of ZIS, tracing key decision points for water distributions and the kind of arrangements made at these points. This is described as the water flows: from the reservoir down to the farmers, first considering farmer requirements.

The Target—Meeting the AWD Demands

On-farm water-saving practices have been scientifically developed over time to reduce irrigation application requirements and to improve the growing conditions, thereby increasing yield. The practice calls for frequent light irrigation applications until late tillering. During this initial period, water levels on the field can drop until the soil is saturated (the soil is exposed) and then another irrigation application is required. During late tillering, a mid-season drainage is required. After late tillering, a series of wet and dry cycles is repeated until the milk ripening stage after which the soil can further dry to levels below saturation (see figure 1).

Figure 1. Graphical description of AWD irrigation regime.



Given the variability in evaporative demand and rainfall, meeting such a schedule requires care and precision even under controlled conditions. In a large canal irrigation system the target is particularly difficult. A very flexible system in rate, duration and frequency is required to meet the irrigation requirements. An on-demand system, where water is delivered shortly after it is ordered would be ideal to meet such requirements. Farmers could predict when water is needed and order the volume required. If it rains they could delay the order. A rotation system would not work so well because farmers would not be easily able to turn off the water (they could divert it away from their fields, but this would counter benefits gained from reduced applications). Providing the required flexibility seems a daunting task in a large canal system serving thousands of smallholder farmers with variable demands.

Two questions arise: i) To what extent do farmers at Zhanghe practice WSI (i.e., what are the on-farm practices)? and ii) What are canal-management and water-management practices, and how do they influence on-farm practices?

Farmer Practices

The first step is to understand actual farmer practices. Detailed measurements were taken on six farmer's fields in TL and WJX (described in chapter 6 of this publication). Additionally, water levels were measured in 12 fields in the mezzo sites. Figure 2 represents farmer practices in a typical field. The remainder of the results is presented in the annex to this paper.

Immediately apparent is that farmers do not practice an ideal system as presented in figure 1, and as expected there is high variability in practices. But certain key elements of WSI practices exist, and certain patterns emerge. Farmers do not require standing water all the time. They let water levels drop to the field surface but do not allow it to remain at this level for periods longer than a few days except during the period of mid-season drainage.

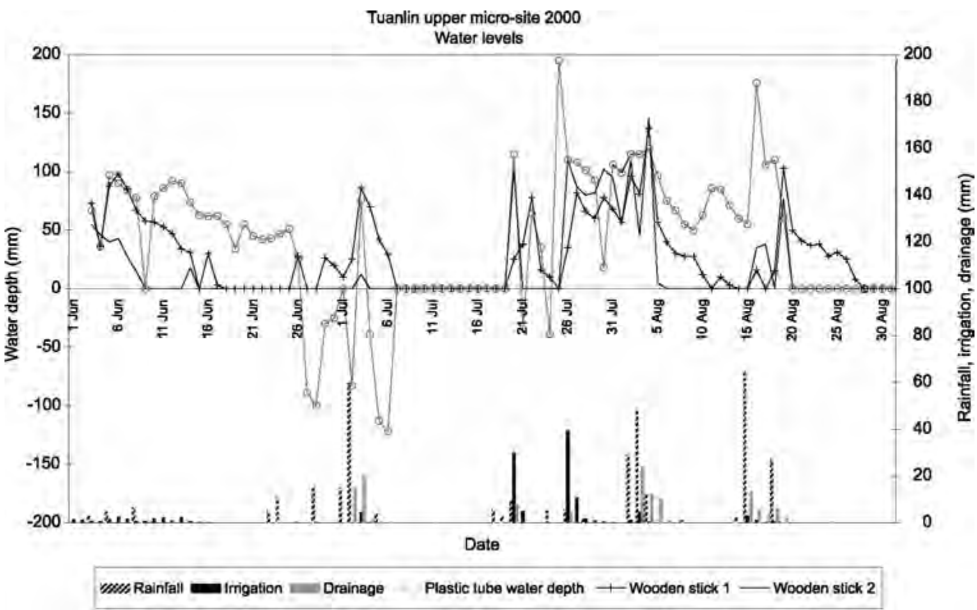
From the water level measurements in 2000, it becomes clear that most farmers practice mid-season drainage. If there is rain during the mid-season drainage period, it looks as if some farmers opt to store the rainwater in their fields instead of letting it drain off. One explanation is that they perceive more benefits from keeping the water and thus not having to pay for additional supplies, rather than draining it and having to obtain supplies later. Farmers do not actually drain their fields for the mid-season drainage, but let them dry out for a period. In 1999, the mid-season drainage was not so obvious as in 2000, which can be attributed to less-accurate measurements and rainfall in the period.

The TL farmers come closer to meeting the ideal AWD practice than WJX farmers. We frequently heard that this was due to the flat topography and the ease of access to water sources in TL, as opposed to the hilly terrain, more difficult access to water and light soils in WJX.

Farmers capture all rainfall possible and only drain it if the rainfall is very high. The irrigation schedule is very well adjusted to this capturing of rainfall and farmers rarely irrigate directly after rainfall.

How is the canal managed? Do operations facilitate on-farm requirements? The next section focuses on allocation and distribution from the reservoir to the farmer's fields.

Figure 2. Water levels on the upper micro-site in TL in 2000.



Decision Making on Allocation of Water among Sectors at the Zhanghe Reservoir

At the beginning of the irrigation season (end March, begin April) the Zhanghe Irrigation Administration Bureau makes a long-term forecast allocation plan based on irrigated area, weather forecast and the condition of water sources (mainly storage in the main reservoir). The result is an overall scheme for water allocation and distribution.

In the beginning of the irrigation season, the Zhanghe Administration Bureau sends water application forms to the main canal sections that pass them on to the stakeholders in their command area (townships and villages), which subsequently pass them on to the water users. Farmers can fill in their demand for the coming irrigation season. The forms are returned and a calculation is made of the total demand and the amount to be allocated to the different main canals. In a normal year, farmers are allocated the amount they request.

After this, a more detailed allocation and distribution plan is made in meetings (30 to 40 people attending) with the heads of both the main-canal section and canal, and others.

In general, the Zhanghe Irrigation Administration Bureau decides on the amount of water allocated to each sector, with one exception: during the flooding season, the Hubei Provincial Government has the power to decide on the amount of water to be allocated to hydropower and flood-control release. The water for hydropower is recycled for irrigation and municipal use outside of ZID. This water flows into the Juzhang river from a different outlet from the reservoir than the irrigation water.

The objective of water supply is not only subordinate to flood control but also a prerequisite for reservoir safety. As much water as possible is stored to meet water demand for all users, but irrigation has first priority and all other sectors (hydropower, industries and municipalities) receive water after the irrigation requirements are met. However, in general, the Zhanghe reservoir has enough water to fulfill all requirements.

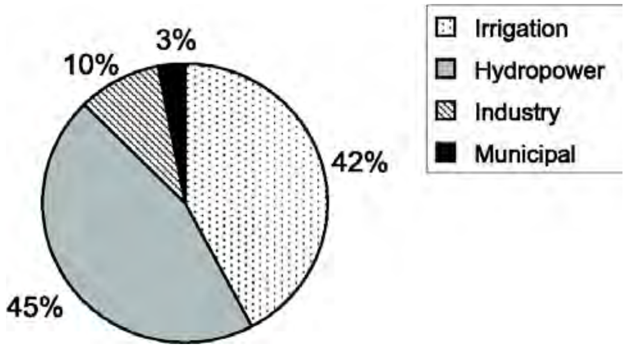
In a normal year, about half of the total water releases of the Zhanghe reservoir are allocated to irrigation (table 3 and figure 3).

Table 3. Annual Zhanghe reservoir inflow and releases (average in 1989–1998).

Sector	Amount (mcm)
Irrigation	211
Hydropower	225*
Industry	48*
Municipal	15*
Inflow	927**

* No data available from 1998.
** No data available from 1997 and1998.

Figure 3. Sector water allocation, Zhanghe reservoir (average values for 1989–1998).



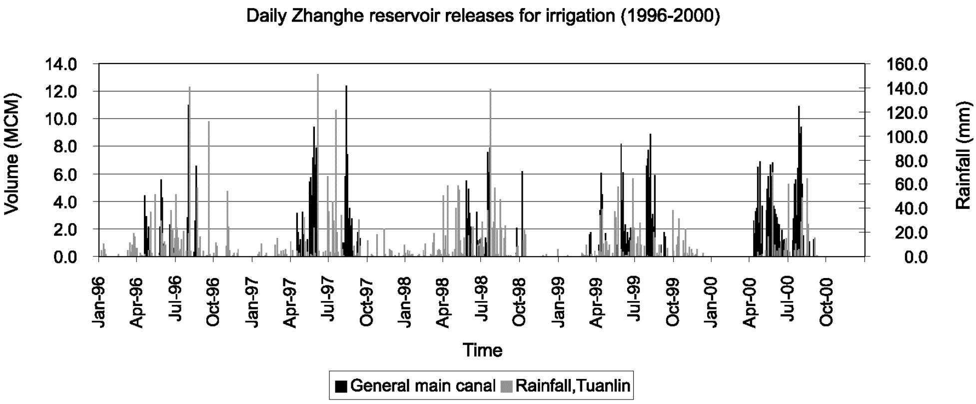
Timing and Amount of Water Releases from the Zhanghe Reservoir

There is an annual meeting held in April at the main-canal level to discuss the ZIS plan for water releases, financial matters, and issues related to O&M. In the third main canal, the water users are represented at these meetings by representatives from the Irrigation Associations. It is not clear how the water users in the fourth main canal are represented at this meeting. Township Water Resources Bureaus are also represented.

As stated earlier, the timing of the water releases from the reservoir depends on the weather situation. There are usually around three to five releases a year to any given branch canal. While farmers do order water, many of the decisions on when to release water comes from higher levels in the canal-operations hierarchy. Thus it appears that the management of canal water has not only an element of farmer demand but also a strong element of a supply approach where reservoir operators make decisions based on available storage, rainfall, and on an overall view of when crops need water. The ponds and small reservoirs located within the irrigated area allow farmers to get a much more flexible supply of water on-demand. However, if users request to stop the water releases from the reservoir, because of ample supply by rainfall, ZIS will close the gates. The water already flowing in the canals has to be paid for by the users. So the entire system functions as an on-demand system because of its in-built flexibility to store water close to the water users, which is a prerequisite for adopting WSI techniques like AWD irrigation. If we look at figure 4 we see that, in general, there are three to five releases from the reservoir to the general main canal.

After correlating the monthly rainfall with the monthly reservoir release to irrigation over the season, in a scatter diagram it becomes clear that there is a trend that in months with high rainfall the reservoir releases are lower. This is strongest in the period May to August, which is the main period for irrigation.

Figure 4. Daily Zhanghe reservoir releases for irrigation, 1999–2000.



ZIS Operation

Part of ZIS is not directly operated by the Zhanghe Irrigation Administration Bureau itself. The third main canal is managed by the Jingmen City Water Resources Bureau. The second main canal delivers water to Jingmen city, Dang Yang county and Jingzhou city. The third main canal delivers water only to Jingmen city. The fourth main canal delivers water only to the Jingmen prefecture (city, district, county).

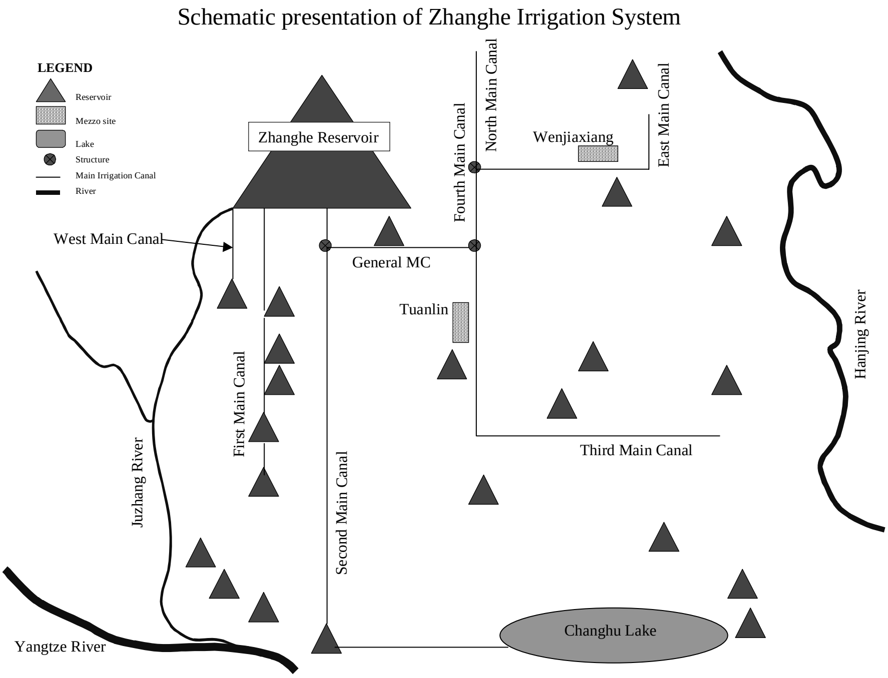
See table 4 for water releases per main canal and figure 5 for details about the distribution network of ZIS.

Table 4. Water releases for irrigation per main canal (average 1989–1998).

Canal	Water release for irrigation (mcm)
General main canal	179*
West main canal	1.8*
First main canal	6.8*
Second main canal	53
Third main canal	101
Fourth main canal	25

*Average values over 1996–2000.

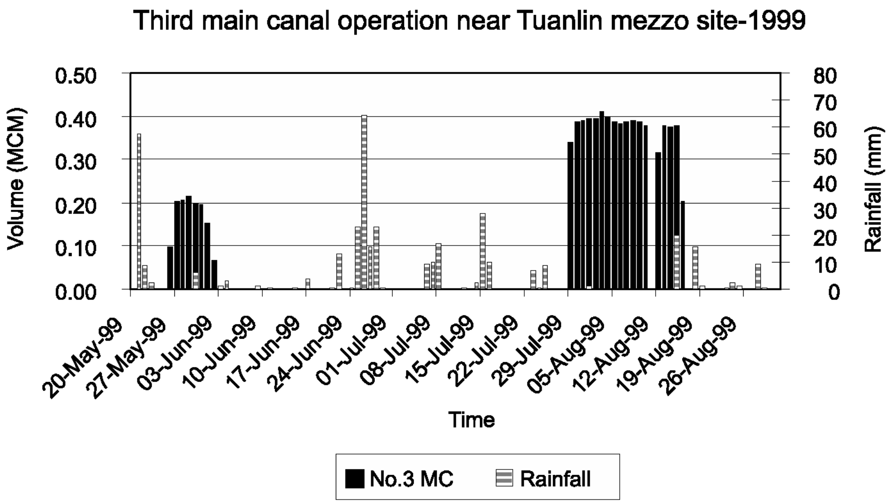
Figure 5. Schematic presentation of the ZIS.



Third Main Canal

The third main canal is not managed by ZIS but by the Jingmen City Water Resources Bureau because most of the command area is within the Jingmen city prefecture limits. In general, the third main canal receives water twice a year for about 20 days in a row. This is considerably less than what the fourth main canal receives, which is explained by the better local water sources (reservoirs and ponds) in the third main canal command area (see also figure 7). In dry years when the demand is higher the number of turns remains the same, but the flow period in the canal is extended. Figure 6 illustrates the daily releases of the third main canal for 1999 and 2000 from which it becomes clear that the releases occur in the same time period in both years.

Figure 6. Daily operation of the third main canal near the TL mezzo site, 1999 and 2000.



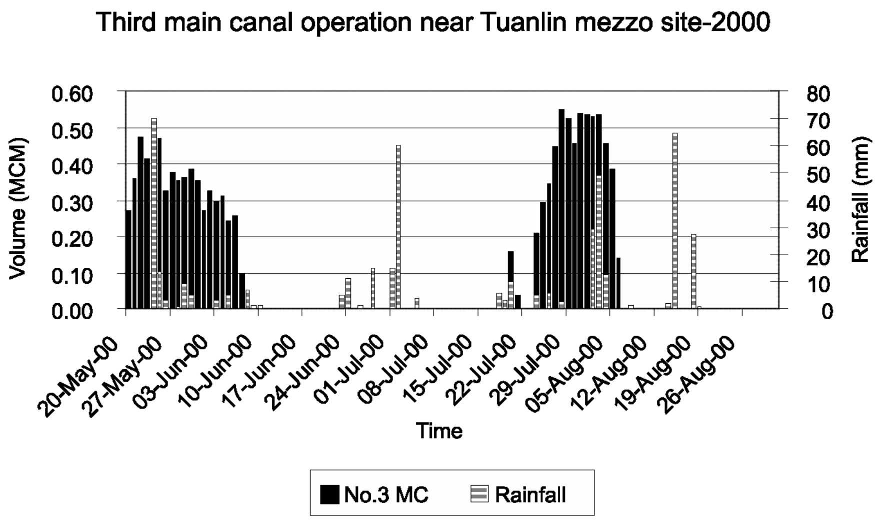


Figure 7. Third main canal water sources.

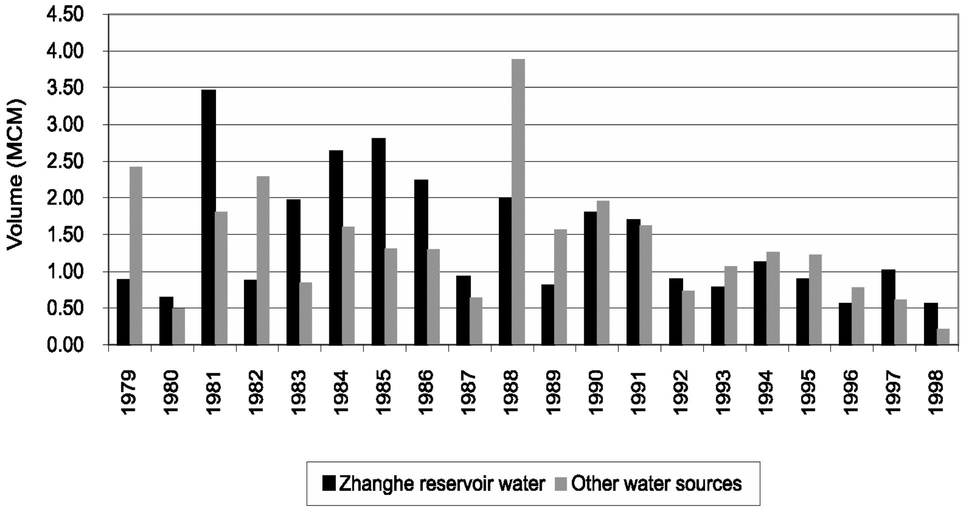


Figure 7 shows the contribution of local water sources to the command area of the third main canal. Note that not all irrigation with local water sources is necessarily on the same area as the Zhanghe reservoir water is also used. There are reports that the third and fourth main canal command areas are partly irrigated by the third and fourth main canal, respectively, and that the other parts of the command area are irrigated with water from local sources.

Fourth Main Canal

The fourth main canal bifurcates into the east main canal (direction of WJX) and the north main canal. It is possible to operate a sort of rotational schedule between the east and the north main canal. However this is rarely done. In the fourth main canal, the priority for allocation is as follows: domestic, industry, agriculture and hydropower. This is different from the priority setting at reservoir level where agriculture gets first priority.

Water requests are handled according to the irrigation-management regulations. Before the irrigation season starts the management divisions of the fourth main canal, townships and counties have a meeting about the provincial government regulations. After this meeting, the management division of the fourth main canal has a one-day meeting from 10 to 15 April with all the users. Three topics are discussed: how much water from ZIS is to be allocated, water use plan for all sectors and how much water is to be allocated to each sector. In general, all demands can be met and it remains unclear how the decision-making process is working during periods of water shortage.

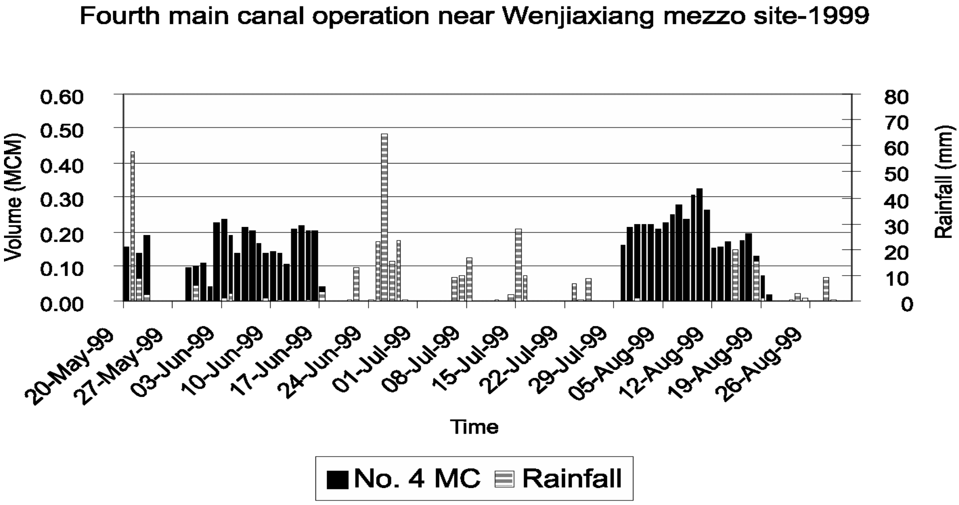
During the irrigation season the water users request water from the sections of the fourth main canal. The section collects all information on demands (volume and timing). The fourth main canal office receives all water requests from all the sections in the fourth main canal and cumulates these after which a request is made to the Zhanghe reservoir to release water. The sections should apply to the fourth main canal office at least 3 days in advance. The fourth main canal office should apply to the Zhanghe Irrigation Administration Bureau at least 2 days in advance. The final decision about water releases from the reservoir remains with the Zhanghe Irrigation Administration Bureau. The periods of water release are almost the same every year. In general, the fourth main canal receives water four times a year (see table 5), because of a longer canal, complex topography and light soils in some parts of the command area: the first time for seedbed preparation, the second time for transplanting and the third and fourth times during the middle rice-growing season. The water in the main canals and branches flows for about 20 days and there is rotation of water among laterals.

Table 5. General timing of water releases to the fourth main canal.

Fourth main canal operation	
Period	Number of days
10–12 April	3
20 May–5 June	10
End of June–early July	10 to 15
10–20 August	10 to 15

Figure 8 shows that the year 1999 has especially deviated from the general schedule of releases as stated by ZIS (table 5). There were two main releases after the middle of May, the first lasting 29 days from 20 May to the middle of June (including 4 days without releases) and the second from the end of July to 20 of August. In 2000, the schedule was much closer to the general proposed schedule, except for an extra release in mid-June, which postponed the planned release by end of June by 3 weeks.

Figure 8. Daily operation of the fourth main canal near the WJX mezzo site in 1999 and 2000.



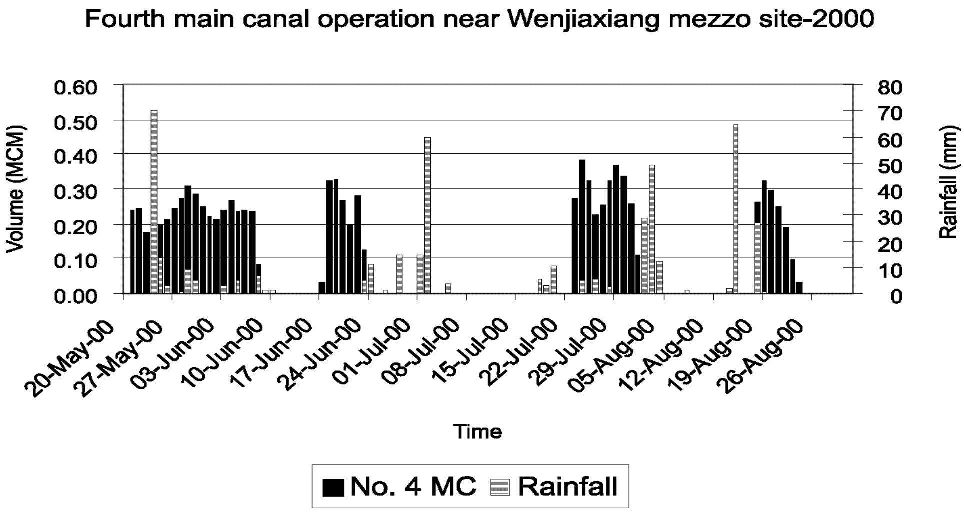
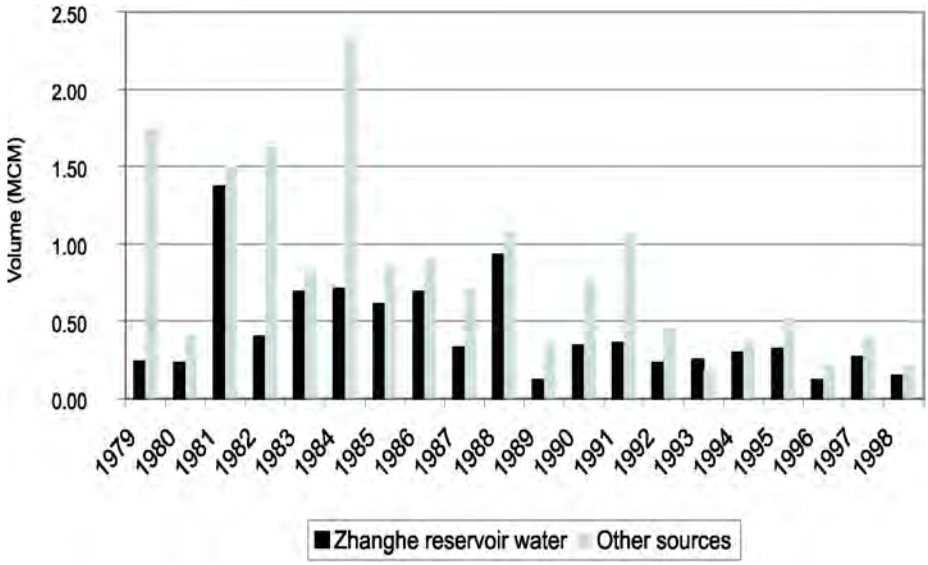


Figure 9 shows the contribution of local water sources to the command area of the fourth main canal. This contribution is lower than in the third main canal but it is still considerable and, in most years, more than that from the Zhanghe reservoir. Note that not all irrigation with local water sources is necessarily on the same area as the Zhanghe reservoir water is also used.

Figure 9. Fourth main canal water sources.



The average volume of "city water" released to the fourth main canal is about is 6 mcm per year. "City water" includes municipal and industrial water. It is taken from the same intake in the fourth main canal. Although it is impossible to differentiate between the two the total volume is known.

Main Canal Section, Township, Village, Group, Farmer

At the level of the main canal there are regular meetings with water users to discuss the water delivery schedule. The Chinese local administration is organized along the line of townships, villages, groups and finally of individuals. Many villages and groups and most of the townships have a contract with the main canal section that specifies the command area, volume of water to be delivered, price and terms of payment. The advantage of having a contract is that it simplifies the application procedure. However, even without a specified contract between water users and ZIS it is possible to receive water.

Tuanlin Mezzo Site

The village has a good relationship with the section. Although they have no contract they just pay and, at the end of the season, they never owe money to the section.

In general, farmers request water either directly from their village head or from their group head who will cumulate the request of the group members and inform the village head. Another path of request is that the group head directly contacts the section office of the main canal. Then the request goes up through the ZIS administrative layers (section, branch, main canal and the Zhanghe reservoir).

The reason for this different path of request is explained by a village head in TL who stated that if some groups within a village are not in good terms with one another it is better that the village head keeps an eye on the requests. On the other hand, it is clear that it is easier for all parties involved that the group head goes directly to the section, because it is easier to manage, especially when the village is big. However, it requires a good organized group. In our mezzo site in WJX, most group heads go directly to the main canal section.

When it rains farmers can request the closure of gates, but they have to pay for the water in the canals (up to 3 days of lag-time). After heavy rains the authorities of the main canal section can close some gates but they have to inform the higher administrative unit directly. Generally, there is a rotational water supply to groups below the village level.

Decision on Allocation of Water for Irrigation in Years of Shortage

During years of extreme water shortage (or flooding) the Flood Control and Anti-Draught (FC&AD) organization, headed by the Vice President of P.R. China, represented in ZIS by the Mayor of Jingmen city, takes over the water management from the Zhanghe Irrigation Administration Bureau and local governments. De facto, there is little difference between this organization and the local government; however, according to some people, it is better that the FC&AD organization gives an order in these times, since they carry more authority. The FC&AD organization gives orders to the second, third and fourth main canal. Local governments and ZIS are represented in the organization. In years with less water shortage, the Zhanghe Irrigation Administration Bureau solves the problems independently by rationing the various canals and branch canals proportionally. On main-canal level the townships are rationed proportionally.

Water Management Service Fee

In this section we explore the flow path of payments for water management services, which is described as the money flows: from the water users up to the Zhanghe Irrigation Administration Bureau. The following different levels are distinguished: the farmers, groups, village and township, the ZIS main-canal section and the Zhanghe Irrigation Administration Bureau.

Farmers

There are two ways farmers pay for water. The first is a flat rate based on area to be paid to the local government. This “water tax” or “basic water fee” is included in the overall tax bill everyone gets from the village. The “flow path” of the basic water fee is from the farmers, to group, to village, to township after which it most likely goes to the county. People have to pay the basic water fee even if they do not use water. There are different reports on the amount of this basic water fee expressed either in yuan per unit area (varying from yuan 2 to 10/mu) or in kilograms of rice per unit area. The second way is a water fee related to the amount of water used and has to be paid to the Zhanghe Irrigation Administration Bureau via different administrative layers. In the following sections the main focus will be on this latter water fee. Almost all the farmers in ZIS pay their water fee on a per area basis. There are reports that farmers pay per volume of water; however this is confined to certain areas. In general, farmers either pay their water fee to their group head or to the village head.

Groups, Village and Township

Groups, village and township pay the water fee on a volumetric basis to the section office of the the ZIS main canal. However, they convert this volumetric fee into an area-based fee for the farmers. Different group heads and village heads, both in the TL and WJX areas, state that, at the end of the season, they calculate the total amount paid to the section office of the ZIS main canal and divide this amount by the total area. After this, the water fee per area is known and is charged to the farmers. There is no money that remains somewhere at this level. Salaries of pump operators or village "water people" are not included in the per-area-based water fee but are paid from other taxes.

There is a big difference between water fees for pumped water and gravity irrigation. In general, the price of pumped water is expressed as an amount of money per hour charged to the farmers. When water is pumped from a ZIS canal, the additional volumetric water fee has to be paid to the section office of the ZIS main canal.

In the TL mezzo site the water fee to the groups is also expressed as a volumetric fee. However, the volume is derived from the recorded time the gate was open and the specific diameter of the pipe. The group head and the irrigator (from the village) go together to the gate and the irrigator opens the gate. Both of them record the time of opening and closure. After harvest, the group head pays to the village according to the calculated volume and the village passes this on to the section office of the ZIS main canal. The group head calculates the total fee paid and divides it by the total area. The farmers pay their water fee on a per-area basis.

There are several statements that the use of water from both small ponds that have no direct connection to ZIS and drainage water is for free. The volumetric water fee from other reservoirs (although they may not be connected to ZIS) is the same as the ZIS volumetric water fee.

There is no visible clear trend over time of the per-area fee since the price depends on the amount of water used by the group or village and this depends on the weather conditions of a particular year.

ZIS Main Canal Section

The ZIS main canal section acts mainly as an intermediary between the group, village and township and the Zhanghe Irrigation Administration Bureau. However, as stated above, many villages and groups and most of the townships have a contract with the main canal section that specifies the command area, volume of water to be delivered, the price and terms of payment. However, even without a specified contract between water users and ZIS it is possible to receive water.

Zhanghe Irrigation Administration Bureau

The Zhanghe Irrigation Administration Bureau is financially independent from the Hubei Provincial Government and is the final recipient of the water fees paid by the water users. However, the Provincial Finance and Pricing Control Bureau determines the price per unit of water per sector. Of late, the price per unit of water has been linked to the price of rice. This is to protect the farmers, since the price of rice has dropped dramatically and the water fee has more than doubled over the last decade (see table 6). Before 1984, the provincial government subsidized the water price, which was a fraction of the current price. After 1984, the reservoirs had to be financially self-sufficient and prices went up according to the regulations of the provincial government. Table 7 shows the water fees per sector in 2000. The price for municipal water is almost double that for irrigation water and the price for industrial water is almost three times that for irrigation water. The revenue from hydropower seems rather low.

Table 6. Agricultural water fee development over time.

	Agricultural water fee
Year	Yuan/m^3
Before 1984	0.007*
1991	0.01610
1992	0.01933
1993	0.02002
1994	0.03126
1995	0.03850
1996	0.04158
1997	0.04235
1998	0.04235
1999	0.04235 (0.0385**)
2000	0.0371**

Source: Fourth main canal office, the Jingmen city.
**Source:* Tongqianshan reservoir.
***Source:* Zhanghe Irrigation Administration Bureau.

Table 7. Water fees in per sector in 2000.

Sector	Water fee (Yuan/m^3)*
Irrigation	0.0371
Municipal	0.068
Industry	0.105
Hydro–old plant	0.017**
Hydro–new plant	0.044

* Exchange rate 2000: US$1.00 = Yuan 8.27.
**Based on 9 m^3 of water to produce 1kWh.
Source: Zhanghe Irrigation Administration Bureau.

According to the fourth main canal office, it is sometimes very difficult to distinguish between water allocated to the municipal and industrial sectors, because the water is taken from the same outlet in the main canal. The fourth main canal calls this water “city water.” For the calculation of the water fee a certain percentage is used to differentiate between the two sectors. In 2000, 23.3 percent of the total volume of city water was allocated to industry. The percentage comes from “the statistics.” It is not clear if the percentage has changed over time. However, it is clear that the use of city water has increased over time.

Discussion and Conclusion

In general, we do have a broad idea of how ZIS is managed on different levels, how the water flows are managed and how the water fees are calculated, collected and passed on to different levels in the ZIS management organization. The closer the water gets to the farm, the more the variability in the operating procedures making it difficult to understand the process.

During the study it was apparent that very few people could explain the entire functioning of this complex system. But it is also apparent that it is not necessary for any individual in the system to know all this. The system has been divided into several layers—reservoir operators, canal operators, townships, villages, farmer groups and farmers. The least a person has to know to be effective are the requirements to get water and make payment to the layer above, and the procedures for passing the water and collecting money from the layer below. Looking as an outsider into this maze, it is amazing that it all works!

The ZIS operates independently from the Hubei Province and has to be financially self-sustainable. However, ZIS has to operate within regulations set by the Hubei Province. These regulations concern mainly the minimum water releases for downstream use and fixed water fees.

On average, in the last decade, the Zhanghe reservoir has allocated about 42 percent of the released water to irrigation, 45 percent to hydropower and the rest to industrial and municipal uses. The reservoir operation is subject to flood control and is a prerequisite for reservoir safety.

On-farm water-saving practices to reduce irrigation application requirements and to improve the growing conditions, thereby increasing yield, call for frequent light irrigation applications until late tillering. During late tillering, a mid-season drainage is required. After late tillering, a series of wet and dry cycles is repeated until the milk ripening stage after which the soil can further dry to levels below saturation.

Given the variability in evaporative demand and rainfall, meeting such a schedule requires care under controlled conditions. In a canal irrigation system though, the target is particularly difficult. A very flexible system in rate, duration and frequency is required to meet the irrigation requirements. An on-demand system, where water is delivered shortly after it is ordered would be ideal to meet such requirements. Providing the required flexibility seems a daunting task in a large canal system serving thousands of smallholder farmers with variable demands.

The timing of the water releases from the Zhanghe reservoir depends on the weather situation. There are usually around three to five releases a year to any given branch canal. While farmers do order water, many of the decisions on when to release water come from higher levels in the canal operations hierarchy. Thus it appears that management of canal water has not only an element of farmer demand but also a strong element of a supply approach where reservoir operators make decisions based on available storage, rainfall, and on an overall view of when crops need water. The ponds and small reservoirs located within the irrigated area allow farmers to get a much more flexible supply of water on-demand. However, if users request to stop the water releases from the reservoir because of ample supply by rainfall, ZIS will close the gates. The water already flowing in the canals has to be paid for by the users. So the entire system functions as an on-demand system because of its in-built flexibility to store water close to the water users, which is a prerequisite for adopting WSI techniques like AWD irrigation.

The contribution of local water sources to irrigation is high. For the fourth main canal it is, in most years, more than the contribution from the Zhanghe reservoir. However, not all irrigation with local water sources is necessarily on the same area as the Zhanghe reservoir water is also used. There are reports that the third and fourth main canal command areas are just partly irrigated by the third and fourth main canals, respectively, and that the other parts of the command area are irrigated with water from local sources. The small ponds located close to the farmers' fields are not accounted for in official statistics, but from our observations, their contribution to irrigation is quite high.

Actual farmer practices show that they are not able to follow the theoretical AWD techniques and, as expected, there is high variability in practices. But certain key elements of AWD practices exist and certain patterns emerge. Farmers do not require standing water all the time. They let the water level drop to the field surface but do not allow the level to remain for periods longer than a few days except during the period of mid-season drainage.

From the water-level measurements at the field it becomes clear that most farmers practice mid-season drainage. If there is rain during the mid-season drainage period, it seems that some farmers opt to store the rainwater in their fields instead of letting it drain off. One explanation is that they perceive more benefits from keeping the water, and thus not having to pay for additional supplies, rather than draining it and having to obtain supplies later. In 1999, the mid-season drainage was not so obvious as in 2000, which can be attributed to less-accurate measurements and rainfall in the period.

The TL farmers come closer to meeting the ideal AWD practice than the WJX farmers. We frequently heard that this was due to the flat topography and the ease of access to water sources in TL against the hilly terrain, more difficult access to water and light soils in WJX.

Farmers capture all rainfall possible and only drain it only if the rainfall is very high. The irrigation schedule is very well adjusted to this capturing of rainfall and farmers rarely irrigate directly after rainfall.

There are two ways farmers pay for water. The first is a flat rate based on area to be paid to the local government. This "water tax" or "basic water fee" is included in the overall tax bill everyone gets from the village. People have to pay the basic water fee even if they do not use water. The second way is a water fee related to the amount of water used, which has to be paid to the Zhanghe Irrigation Administration Bureau via different administrative layers. In general, farmers either pay their water fee to their group head or to the village head.

Groups, village and township pay the water fee on a volumetric basis to the section office of the ZIS main canal. However, they convert this volumetric fee into an area-based fee for the farmers, by calculating the total amount paid to ZIS and dividing this amount by the total area.

The section office of the ZIS main canal acts mainly as an intermediary between groups, village and township and the Zhanghe Irrigation Administration Bureau. However, many villages and groups and most of the townships have a contract with the section office of the main canal that specifies the command area, volume of water to be delivered, the price and terms of payment. Even without a specified contract between water users and ZIS it is possible to receive water.

The Provincial Finance and Pricing Control Bureau determines the price per unit of water per sector. Of late, the price per unit of water has been linked to the price of rice to stabilize the water fees. The water fee has more than doubled over the last decade. Before 1984, the provincial government subsidized the water price, which was a fraction of the current price. After 1984, the reservoirs had to be financially self-sufficient and prices went up according to the provincial regulations. There is no visible, clear trend over time of the per-area fee, since the price depends on the amount of water used by the groups or village and this depends on the weather conditions of a particular year.

The use of water from both small ponds that have no direct connection to ZIS and drainage water is for free. The volumetric water fee from other reservoirs, which may not be connected to the ZIS, is the same as the ZIS volumetric water fee, since the price is set for the whole Hubei Province by the Provincial Finance and Pricing Control Bureau.

Some of the very strong points of the design and operation of this system are:

1. The division of the task of delivering water into several layers. It is not necessary for the main canal operators to deliver water to farmers. More decentralized decisions are made to better meet farmer needs.

2. Clear rules or understanding has developed at each point of water transfer and money transfer.

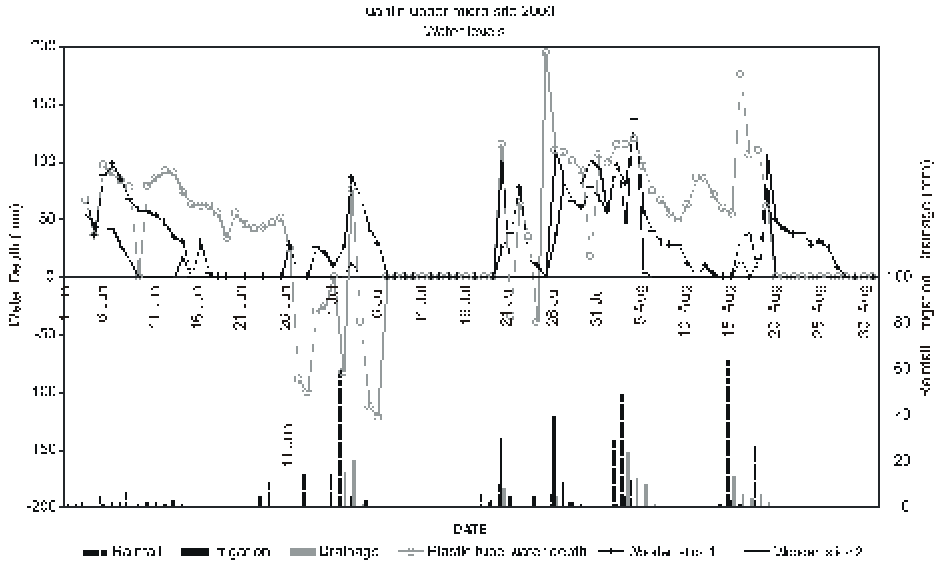
3. The strategy of making a few deliveries from the main reservoir at somewhat predictable intervals.

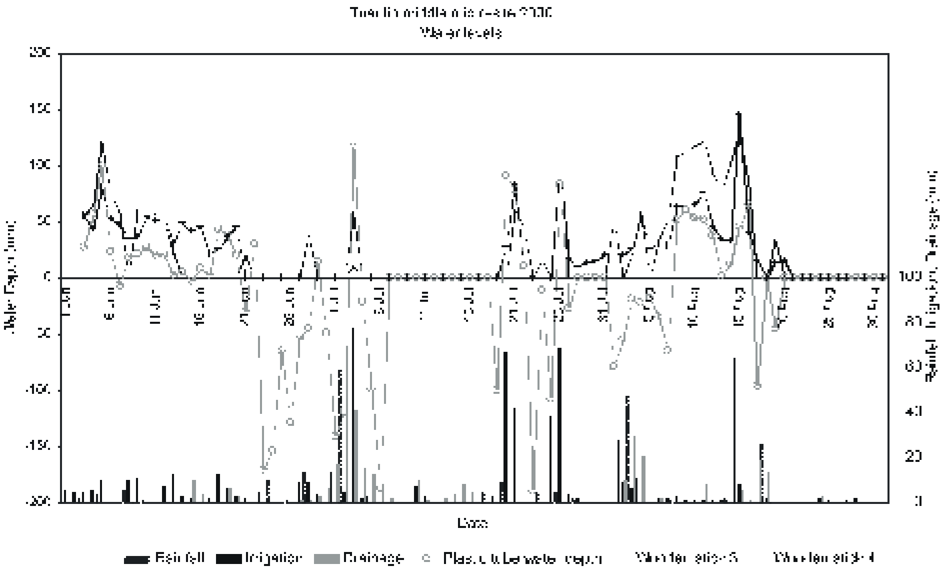
4. The reliance on local sources for flexibility.

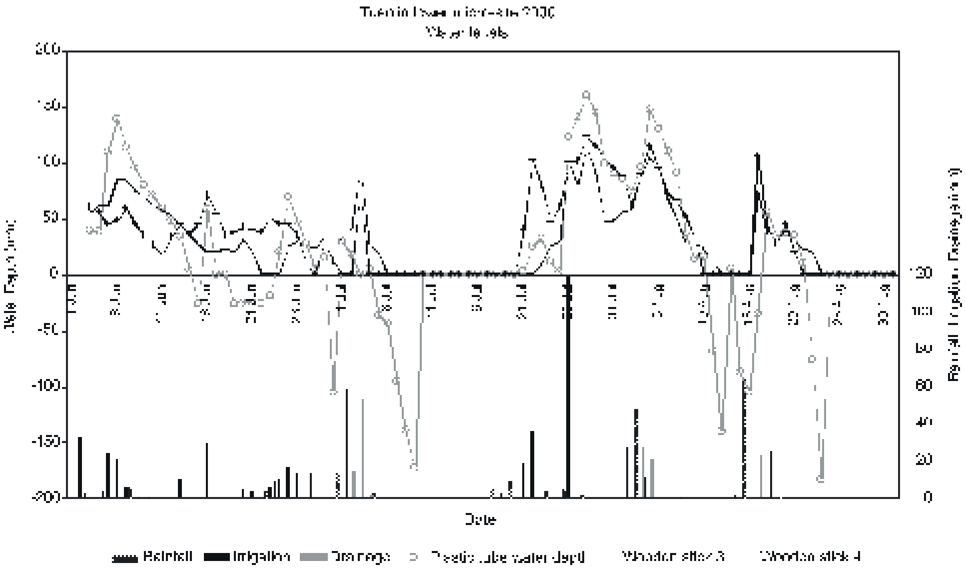
In our discussion with farmers, we found that an area that requires improvement is the communication to farmers when water is released. Several farmers were unsure of the timing of canal releases.

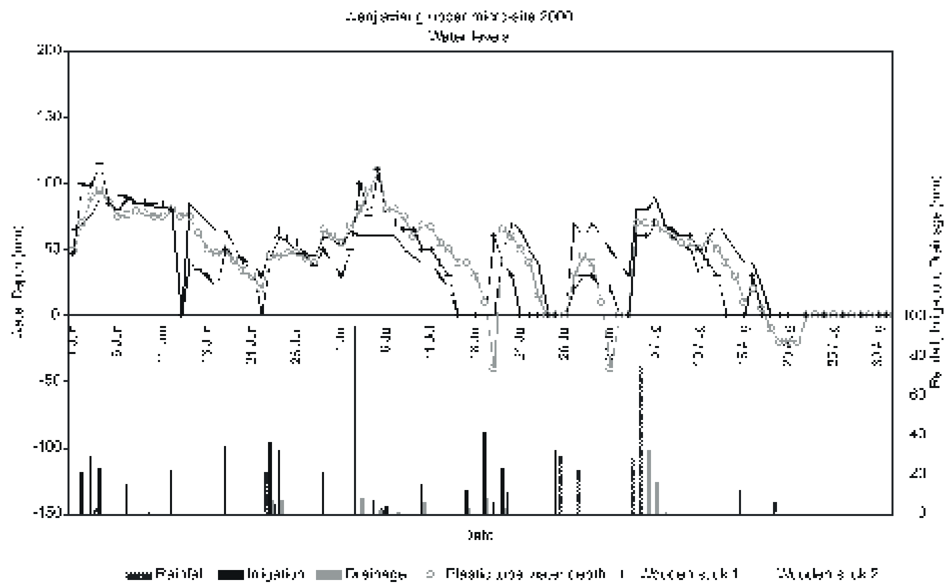
Annex

Water level graphs of selected micro-sites in 1999 and 2000.






Water levels
200
150
100
50
0
-50
-100
-150
-200
120
100
80
60
40
20
0
Date
Rainfall
Irrigation
Drainage
Wooden stick 3
Wooden stick 4


Water levels
200
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-50
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-150
100
80
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20
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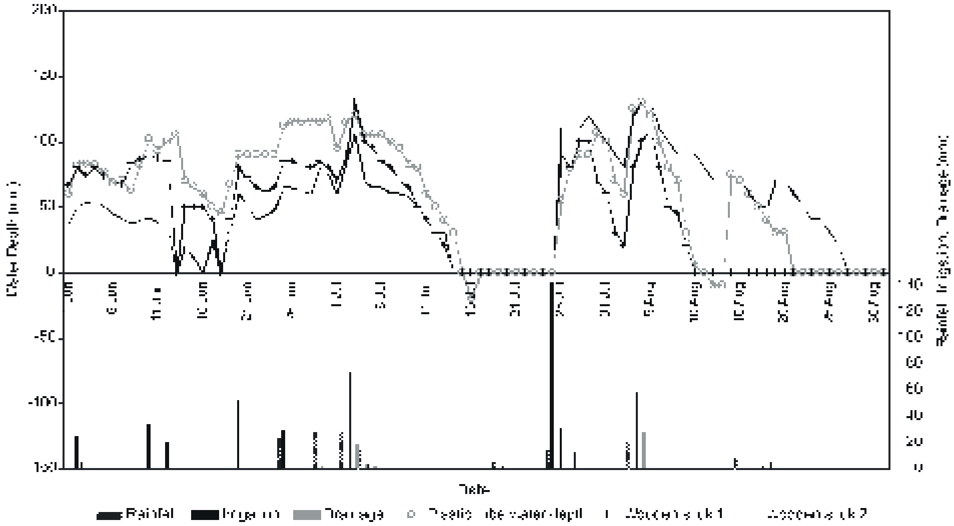
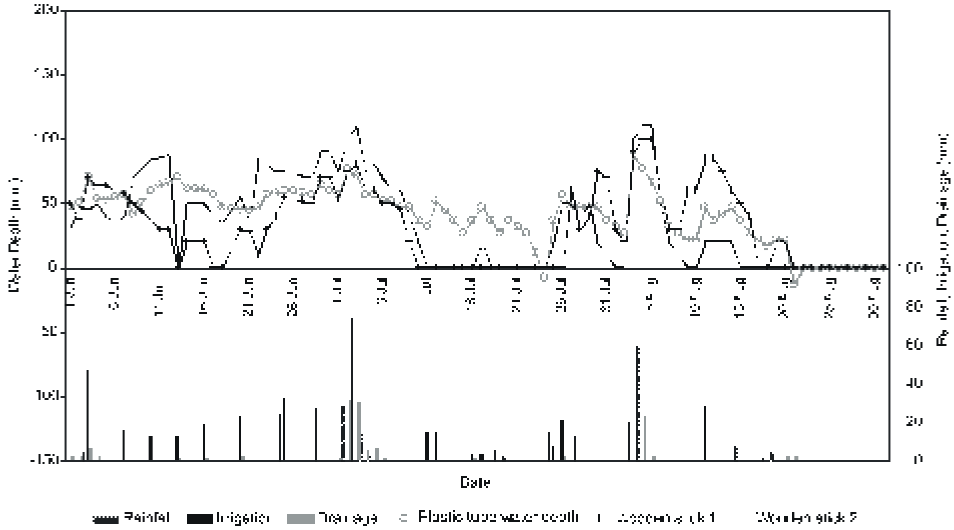
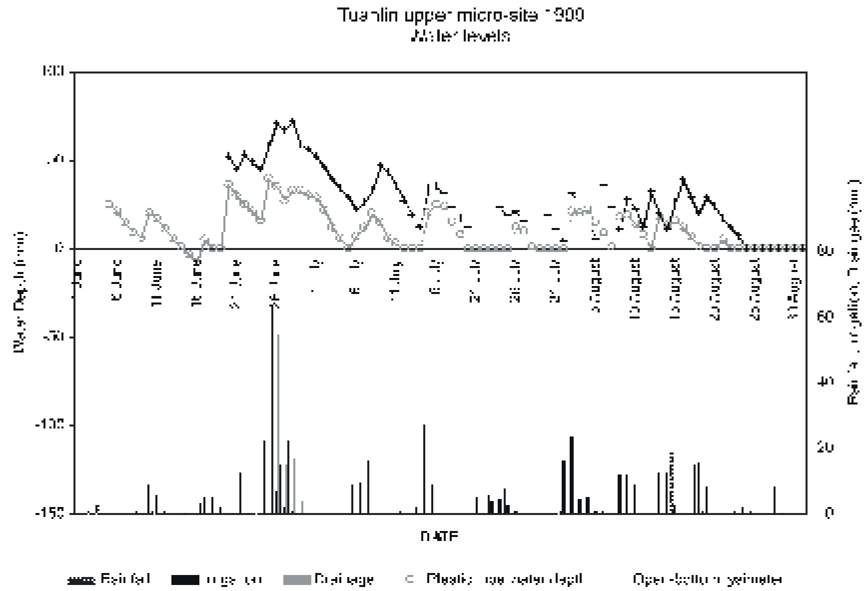
Date
Rainfall
Irrigation
Drainage
Wooden stick 1
Wooden stick 2

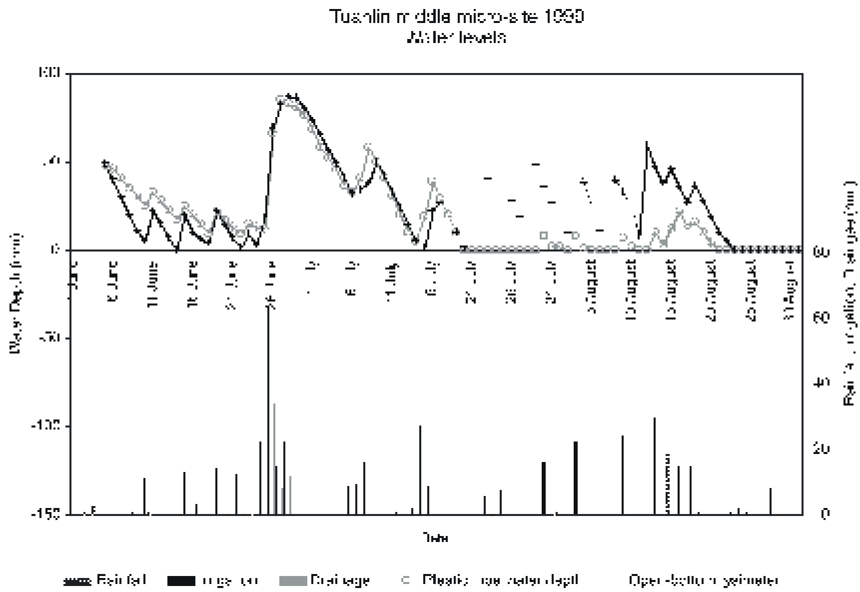
Wenjiaxiang middle micro-site 2000
Water levels



Wenjiaxiang lower micro-site 2000
Water levels




Tuanlin upper micro-site
Water levels
Water Depth (mm)
100
50
0
-50
-100
-150
DATE
Rainfall
Drainage
Plastic tube water depth
Open-bottom lysimeter


Tuanlin middle micro-site
Water levels
Water Depth (mm)
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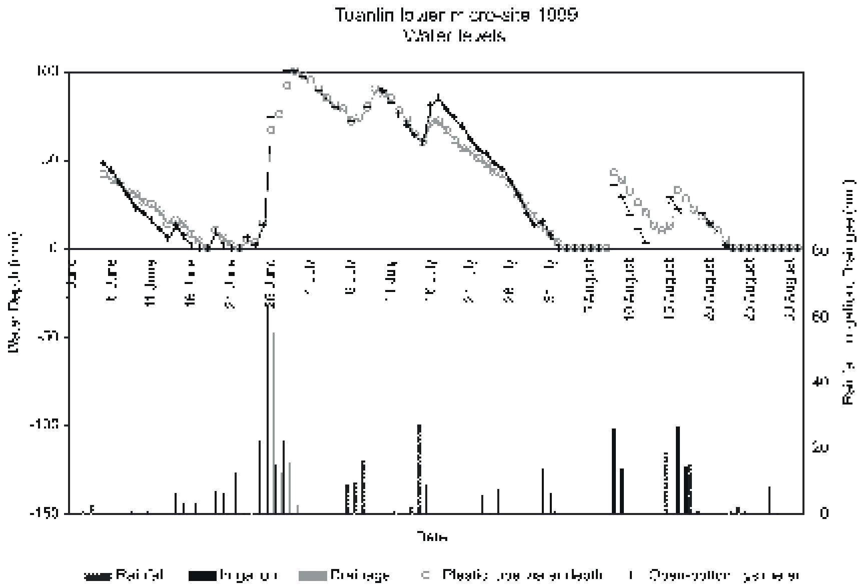
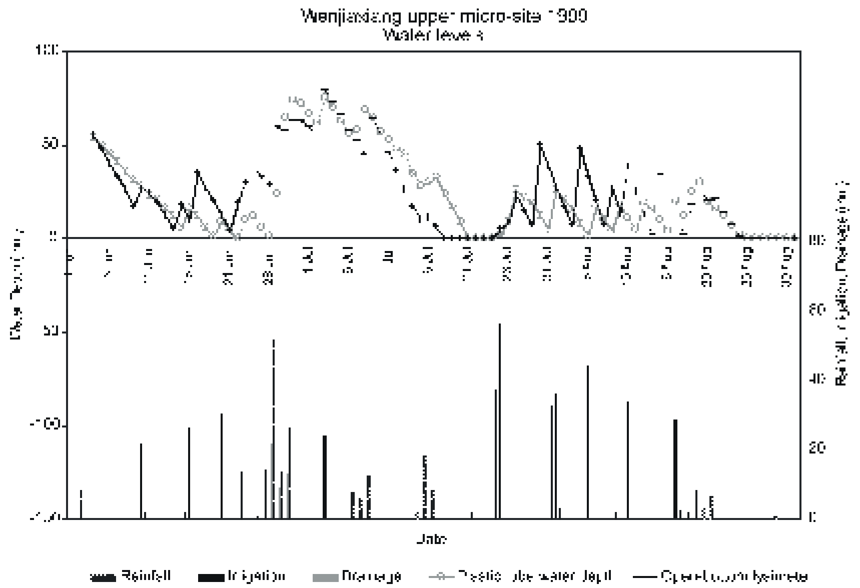
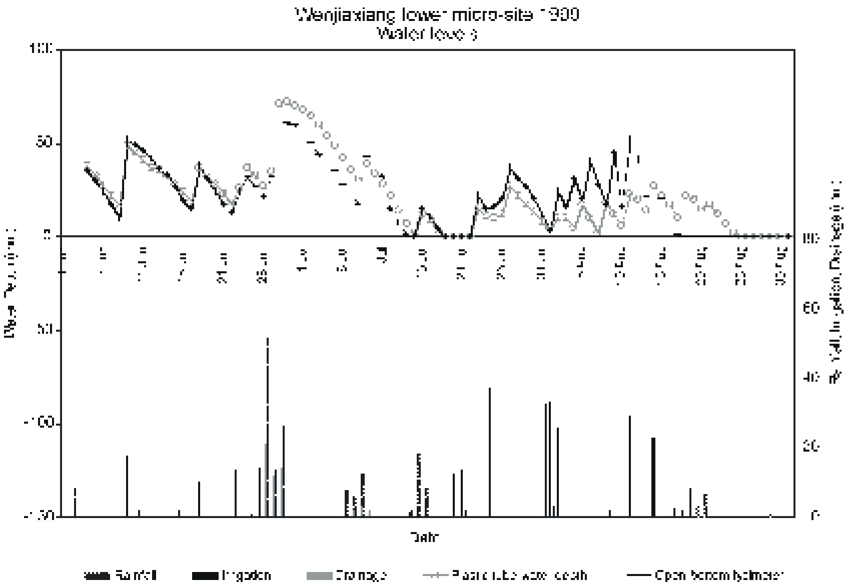
Date
Rainfall
Drainage
Plastic tube water depth
Open-bottom lysimeter


Tuanlin lower micro-site 1999
Water levels
Date
Rainfall
Irrigation
Drainage
Plastic tube water depth
Open-bottom lysimeter


Wenjiaxiang upper micro-site 1999
Water levels
Date
Rainfall
Irrigation
Drainage


Wenjiaxiang lower micro-site
Water levels
100
50
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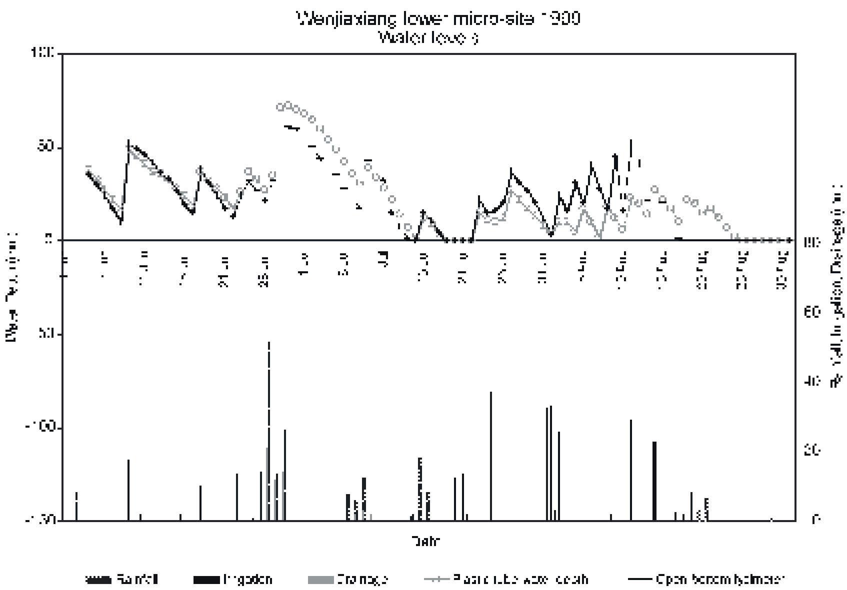
Date
Rainfall
Irrigation
Drainage
Plastic tube water depth
Open bottom lysimeter


Wenjiaxiang lower micro-site
Water levels
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Rainfall
Irrigation
Drainage
Plastic tube water depth
Open bottom lysimeter

Literature Cited

B. Dong; R. Loeve; Y. H. Li; C. D. Chen; L. Deng; and D. Molden. 2001. Water productivity in the Zhanghe Irrigation System: Issues of scale. In *Proceedings of Workshop on Water-Saving Irrigation for Rice.* Wuhan, 23–25 March 2001.

Chapter 4

Impact of Alternate Wetting and Drying Irrigation on Rice Growth and Resource-Use Efficiency

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Abstract

The objective of this study was to quantify the impact of alternate wetting and drying irrigation (AWD) and timing of N-fertilizer application on rice growth, water input, water productivity and fertilizer-use efficiency. The experiment was carried out in 1999 and 2000 in Jinhua, Zhejiang Province and in Tuanlin (TL), Hubei Province, following a split-plot design. The main plots were 2 water treatments (W_1 = AWD irrigation, W_2 = continuous flooding). The subplots consisted of four N-application treatments (F_0 = control, no N fertilizer; F_1 = 2 splits, as farmers practice; F_2 = 4 splits and F_3 = 5 or 6 splits depending on the season). The total N input in all seasons was 150 and 180 kg N ha^{-1} in Jinhua and TL, respectively.

Grain yields varied from 3.2 to 5.8 tons ha^{-1} in Jinhua, while higher grain yields were obtained in TL (4.5 to 9.1 tons ha^{-}). In both sites, there were no significant water-nutrient interactions on grain yields, biomass and N uptakes. In most cases, continuous flooding gave 1–7% higher yields than AWD, but the reverse was true in TL for 2000. However, the difference in yield was not statistically significant at 5% level. The AWD reduces irrigation water compared to continuous flooding. The differences were statistically significant only in 2000 when rainfall was low and evaporation demand was high. Water productivity in terms of irrigation water was about 5–35% higher under AWD than in continuous flooding but differences were significant only in the year 2000.

Increasing the number of splits to 4–6 times (i.e., F_1–F_3) increased the total N uptake, but not grain yield and biomass compared to farmers' practices of 2 splits. This may reflect the inability of the studied rice varieties to convert N taken up into grain.

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We concluded that under the experimental conditions, AWD irrigation did not reduce rice yield but increased the water productivity. This increase may become more pronounced in drier conditions. The AWD did not require a different N-fertilizer management from continuous flooding.

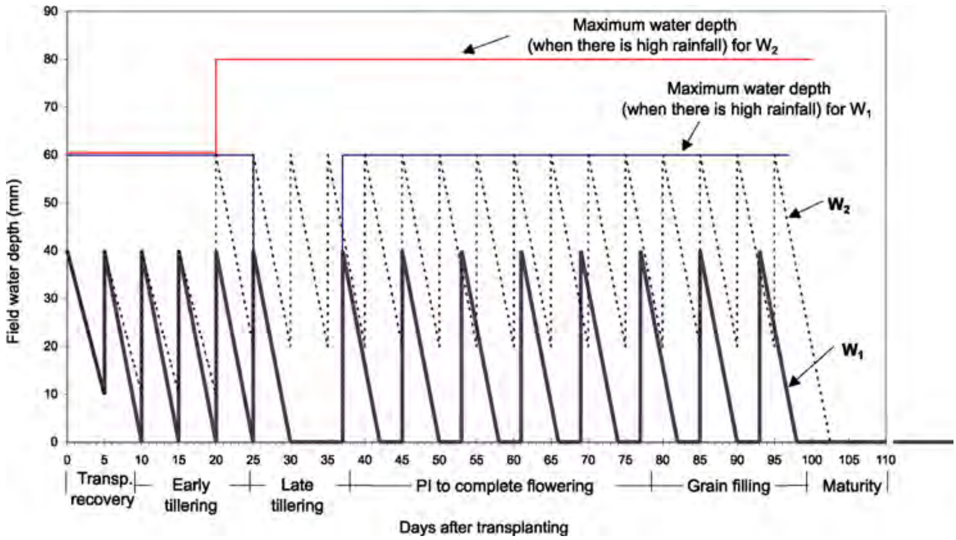
Introduction

Irrigation has played a critical role in the increase of rice production in China. Irrigated rice produces 96% of the annual rice production of 130.6 million tons in 1990 (Rosegrant et al. 1995)**.** Despite having the most intensive rice irrigation in the world, per capita freshwater availability in China is among the lowest in Asia. Rapid industrialization and urbanization will further divert water from agricultural use. The need for “more rice with less water” is crucial for food security and is more urgent in China than in many other Asian countries.

Recognizing the severity of the situation, the government and the people of the P. R. China have already pioneered various water-saving irrigation (WSI) technologies to achieve more water-efficient irrigation for rice-based systems. One of the most commonly practiced WSI techniques is AWD irrigation. This irrigation method is characterized by a) a mid-season drainage during the late tillering stage of the crop and b) periodic soil drying of 2–4 days in between irrigation events from panicle initiation (PI) on to harvest (figure 1). In the mid-season drainage, the soil is dried out for 10–15 days, depending on the weather condition until some fine cracks appear at the soil surface (Mao Zhi et al. 2000), Xu (1982), Wei and Song (1989) and Mao Zhi (1993a) reported that mid-season drainage and intermittent drying of the soil improved rice yield compared to the traditional irrigation practices with continuous flooding. In fact, the superiority of the AWD irrigation in terms of yield has been reported as one of the main reasons for farmers’ acceptance of the new technology. A combination of reduced water input and increased yield resulted in substantial increases in water productivity with respect to irrigation water. The increase in yield under AWD irrigation in China substantially differs from the results reported elsewhere (e.g., Mishra et al. 1990; Tabbal et al. 1992; Bouman and Tuong 2001). Most of the Chinese literature attributes the increase in yield by AWD irrigation to the improvement of the microenvironment of the root zone. There is, however, no scientific evidence to support this reasoning. One possible hypothesis is that, compared to inbred rice, the hybrid rice varieties used in China are more drought-resistant and make better use of nitrogen fertilizer in the form of nitrate (as a result of the nitrification process taking place during the drying periods of AWD irrigation).

There is also evidence that rice cultivation with AWD irrigation has very low fertilizer-use efficiency. Wang et al. (1998) reported that the N recovery efficiency in China is only about 29% in early rice and 5% in late rice in Jinhua, Zhejiang Province. High nitrogen losses could be due to a combination of the present fertilization practice of applying nearly all the fertilizers within 10 days of transplanting, the AWD irrigation practices with the mid-season drainage and the subsequent wet and dry cycles in the later growth stages. Wang et al. (1997) suggested that the present AWD irrigation techniques and N-application practices in China present an enormous challenge for improving N use efficiency.

Figure 1. Designed field water depths in alternate wetting and drying (W_1) and continuously flooded (w_2) in 1999 and 2000, Jinhua, Zhejiang Province and Tuanlin, Hubei Province, P. R. China.



The authors suggested that the techniques have also raised environmental concern. Systematic research on the efficiency of fertilizer use under different water management techniques has not been carried out in China. We hypothesized that applying N in more splits to better synchronize the N-application and water status in AWD irrigation could increase the efficiency of fertilizer use and water productivity.

This study was conducted with the general objective of quantifying the impact of AWD irrigation practices on rice growth and resource-use efficiencies, so as to identify the optimal combination of water and N-fertilizer management. The specific objectives of the study were to quantify rice growth and yield as affected by water management and fertilizer treatments, to compare the amount of water diverted to rice fields and water productivity under AWD and under continuous flooding, and to quantify the recovery and agronomic efficiency of applied N, P and K as affected by fertilizers and the water regime.

Materials and Methods

Experimental Site

The experiments were conducted in 1999 and 2000 at two sites: Jinhua, Zhejiang Province, and TL, Hubei Province, P. R. China. In Jinhua, the experiments were conducted during the early rice (ER) season (March–July) and the late rice (LR) season (June–October). In TL, the experiment was carried out during the mid-season rice crop from May to September. The 20-cm topsoil layer in Jinhua was silt loam and in TL it was clay loam with other characteristics shown in table 1.

Table 1. Soil characteristics of the 20-cm layer, Jinhua and Tuanlin, 1999–2000.

	Jinhua, Zhejiang Province	TL, Hubei Province
Soil type	Silt loam	Clay loam
pH (1:1 H20)	4.7	6.5
Organic carbon (%)	2.03	1.03
Available N (mg kg^{-1})	178	5.8
CEC (cmol kg^{-1})	7.8	20.6

Note: CEC=Cation Exchange Capacity.

Experimental Design and Cultural Practices

The experiments were conducted in a split-plot design with three replications. In TL, a fourth replication was added in 2000. The main plots had two water treatments: (W_1) = AWD and (W_2) = continuous flooding throughout the entire duration of crop growth. The designed water levels in the experiment are shown in figure 1. The subplots consisted of 4-N application timings:

- F_0 = No N application. However, in TL 1999, due to an experimental error, the whole dose of N was applied as basal. Therefore, we indicate the 1999– “control” as F_0*.
- F_1 = Farmers’ practice of two applications. 50% of total N was applied one day before transplanting, and 50% 10 days after transplanting (DAT),
- F_2 = Four applications. 30% of total N as basal, 30% at 10 DAT, 30% at PI and 10% at heading.
- F_3 = N-application timings were adjusted to reduce the amount of fertilizer applied at the beginning of the crop. In 1999, this treatment consisted of six applications in both sites: 25% of total N as basal, 25% at 10 DAT, 20% at PI, 10% just before heading, 10% after heading and 10% after complete flowering. In 2000, due to the objection of farmers (owners of the experimental fields) that the 6-split application was too laborious, F_3 was modified to 4-split applications in the early and mid-season rice crops (17% of total N as basal, 20% at 16 DAT, 27% at mid-tillering stage, and 36% at PI), and 5-split application in late-season rice crop (10% as basal, 17% at 16 DAT, 27% at mid-tillering stage, 36% at PI, and 10% at heading).

Nitrogen was applied as urea at the rate of 150 kg N ha^{-1} in Jinhua, and 180 kg N ha^{-1} in TL. Other fertilizers at both sites were 25 kg P ha^{-1} (single superphosphate), and 70 kg K ha^{-1} (KCl) applied and incorporated into individual plots as basal dressing.

All varieties used were hybrid rice.

The subplot area varied from 90 to 200 m^2. All main plots were surrounded by consolidated bunds, equipped with plastic sheets installed to a depth of 0.25 m. Varieties used in Jinhua were V402 (1999) and Xieyou 46 (2000), and in TL, 2you 501 (1999) and 2you 725 (2000). All varieties used were hybrid rice.

Prior to land preparation, weeds were cut and removed from the field. All plots were hoed manually twice across the plots to a depth of 30 cm. The soil was submerged for one week before harrowing and final leveling. Fertilizers for basal dressing were then incorporated one day before transplanting. Seedlings were grown in a wet bed for approximately 32 days and 45 days in Jinhua and TL, respectively, and transplanting was done at two plants per hill with a spacing of 20 cm x 20 cm.

Complete pest control was carried out in all plots to prevent any interference from weeds, diseases or insects that would hinder full quantitative assessment of water X nutrient interactions.

Soil, Water and Climatic Data Measurements

The water depth was measured daily in 40-cm deep x 20-cm diameter PVC pipes installed in each subplot. The bottom (22 cm) of the pipe was perforated with 1-cm diameter holes at 2-cm intervals. The PVC pipes were installed to a depth of 25 cm below the soil surface. The soil inside the cylinder was dug out to a depth of 25 cm to facilitate measurement of the water table below the ground surface.

Each main plot was irrigated separately. During each irrigation event, the flow rate was monitored at 3-minute intervals by a 20-cm cutthroat flume (Jinhua), V-notch weir (TL, 1999) or current meter (TL, 2000) installed at entry points of each main plot. The volume of water applied during an irrigation event was computed by integrating the flow rate with time. The depth of irrigation water applied was computed by dividing the volume of water applied by the area of the main plot.

After a heavy rain, water depths in the plots may exceed the maximum allowable depths. During such conditions, water was drained to maintain the desired water depth. Drainage depth was computed from the field water depth before and after drainage.

The evapotranspiration was computed from the pan-evaporation with values of the crop factor, K_c obtained from Mao Zhi 1992. The amount of seepage and percolation (S&P) was computed as the difference between inputs (irrigation and rainfall) and outputs (evapotranspiration and drainage). The S&P rate was estimated by dividing the S&P by the number of days with standing water.

In TL, daily rainfall, maximum temperature, minimum temperature, radiation and pan-evaporation were recorded daily from the meteorological station located at the experimental site, and other parameters were obtained from a weather station located about 10 km from the site.

Agronomic Parameters and N Uptake

Phenological development was determined for each subplot at PI, heading, flowering (F) and physiological maturity. Samples for total aboveground biomass and total nutrient uptake were taken from the 12-hill area at 15 DAT, 30 DAT, PI, F, and grain filling (GF). At physiological maturity, rice plants from the designated 12-hill area were cut to ground level for yield-component analysis. At full harvestable maturity, plants from an area of 6 m^2 were taken for yield measurements. Subsamples of straw and grain were analyzed for N, P and K. Plants were sampled and processed using the procedure indicated in the Soil and Plant Sampling Measurements Manual (IRRI 1994). The derived parameters below were calculated using equations that follow them:

Nitrogen harvest index (NHI) = $$\frac{GN}{TN} \quad (1)$$

Physiological N use efficiency (PNUE, kg grain/kg N uptake)

$$= \frac{GY \times 0.86}{TN} \quad (2)$$

Agronomic N use efficiency (ANUE, kg grain/kg N applied)

$$= \frac{(GY_F - GY_0) \times 0.86}{N_F} \quad (3)$$

Apparent recovery of applied N (AR, %) = $$\frac{(TN_F - TN_0) \times 100}{N_F} \quad (4)$$

where,

Factor 0.86 is used to convert grain yield (GY) with 14% MC to dry-weight basis,
GY_0 is grain yield (in kg ha^{-1}, 14% MC) without N application (N0),
GY_F is grain yield (in kg ha^{-1}, 14% MC) with fertilizer N application (NF),
TN is total N uptake (in kg ha^{-1}),
TN_0 is total plant N uptake without N application (in kg ha^{-1}),
TN_F is total plant N uptake with fertilizer N application (in kg ha^{-1}),
N_F is fertilizer N applied (in kg ha^{-1}), and
GN is grain N uptake (in kg ha^{-1}).

We did not compute ANUE and AR for TL in 1999 because the experiment did not include 0-N treatment.

Results

Climatic Parameters

Rainfall, evaporation and sunshine hours from transplanting to harvest in the experimented seasons are shown in table 2. In Jinhua, seasonal rainfall ranged from 330 to 810 mm and was higher in early rice than in late rice. There was only a slight difference in evaporation between early and late rice seasons in 1999. However, evaporation in late rice in 2000 was 25% lower than in early rice. While the highest sunshine duration occurred in early rice in 2000, corresponding to the highest evaporation, variations in sunshine hours did not correspond to the variations in evaporation in other seasons. This was because evaporation also depends on other factors such as wind speed and humidity. In TL, the 2000 crop received higher rainfall, evaporation and sunshine hours than the 1999 crop.

Table 2. Climatic parameters from transplanting to harvesting for the early and late rice crops in Jinhua, Zhejiang Province and for the single rice crop in Tuanlin, Hubei Province, P. R. China, 1999 and 2000.

Site	Season	Rainfall (mm)	Evaporation (mm)	Sunshine hours	Duration* (days)
Jinhua	1999 early rice	810	344	438	96
Jinhua	1999 late rice	330	335	488	84
Jinhua	2000 early rice	591	436	616	90
Jinhua	2000 late rice	403	320	497	92
TL	1999	377	335	573	110
TL	2000	447	382	686	111

*From transplanting to harvest.

Water Depths

Figures 2 and 3 give the mean water levels for the AWD and the continuously flooded treatments for Jinhua and TL, respectively. The small standard errors of the means in Jinhua indicate that the experiment was able to impose the water treatments uniformly across the replications. It was not always possible however to maintain the same water depths in all replications in TL, reflected by high standard errors of the mean water levels (figure 3). This was because replications 3 and 4 were at a lower position in the toposequence than replications 1 and 2.

There was a clear difference in the water regime of the two water treatments. Flooding was maintained in the continuously flooded treatment, while there were periods without standing water in the AWD treatment. Because of rainfall we could not strictly follow the designed water depths in the AWD scheme (compare figures 2 and 3 with figure 1). For example, the drying during the mid-season drainage at the maximum tillering stage of the late rice crops in Jinhua was only a few days instead of the 10–15 days as in the design. Frequent drying periods could not be imposed in the early rice crop in Jinhua in 1999 and in TL in 2000. The data indicate the difficulty in precisely implementing the designed AWD irrigation in farmers' fields. Depending on the location of the field in the toposequence, farmers may or may not succeed in realizing the drying periods as designed.

Figure 2. Mean ± SE of water depths (N=12, from 4 subplots and 3 replications) in alternate wetting and drying (W_1) and continuous flooding (W_2) in 4 seasons in 1999 and 2000, Jinhua, Zhejiang, P. R. China.

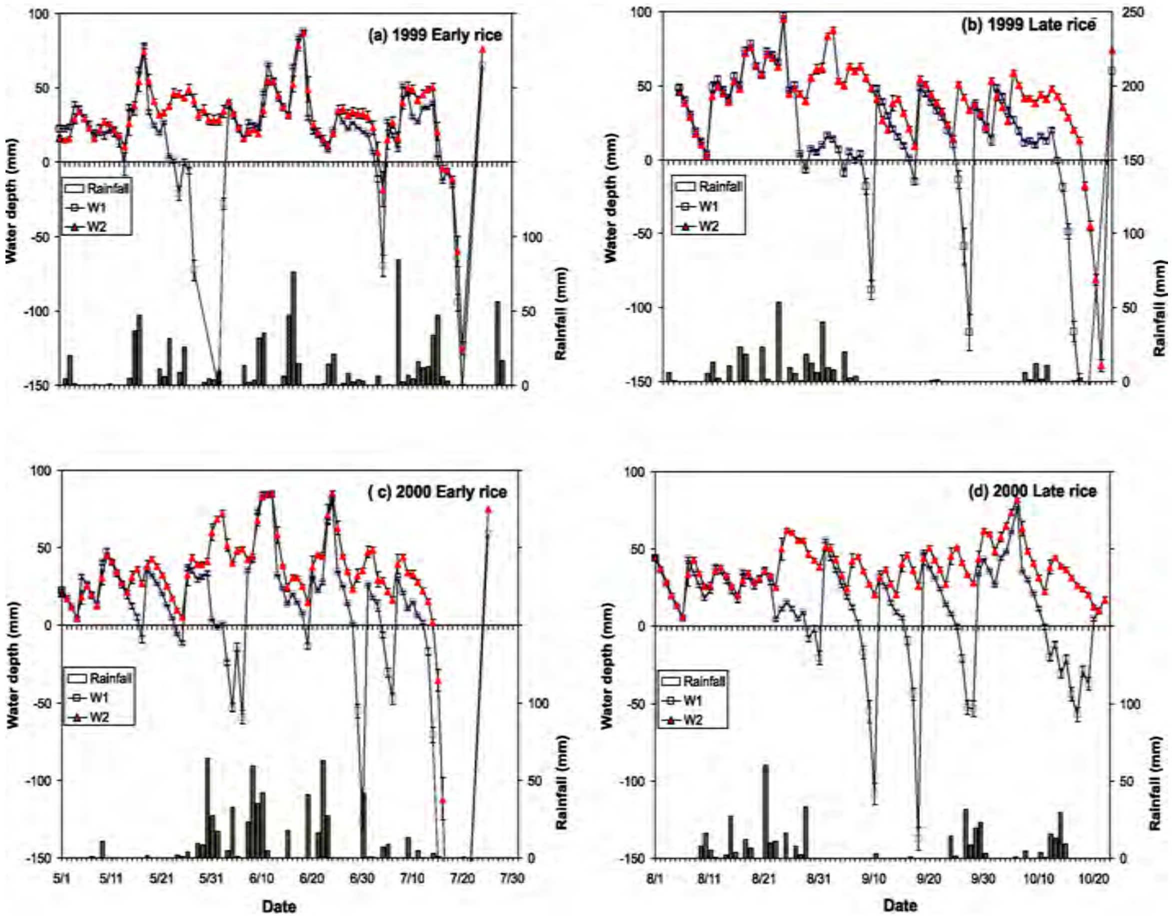
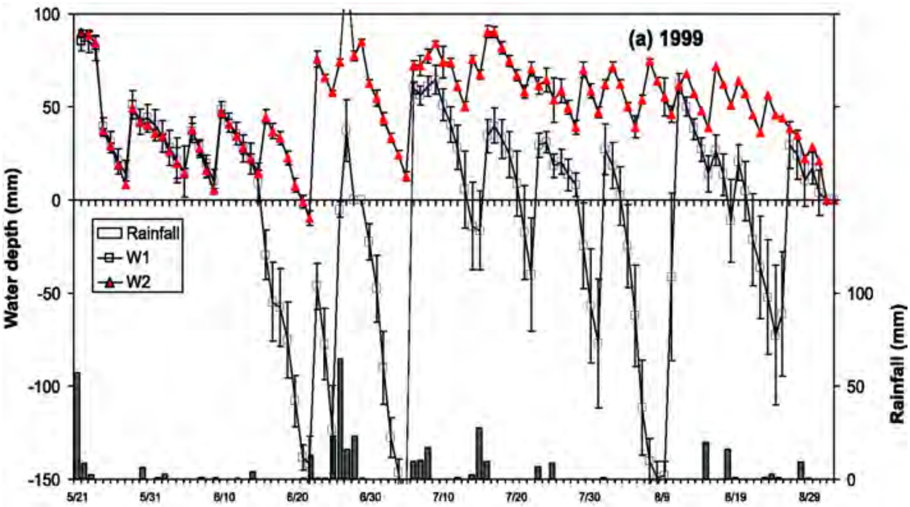
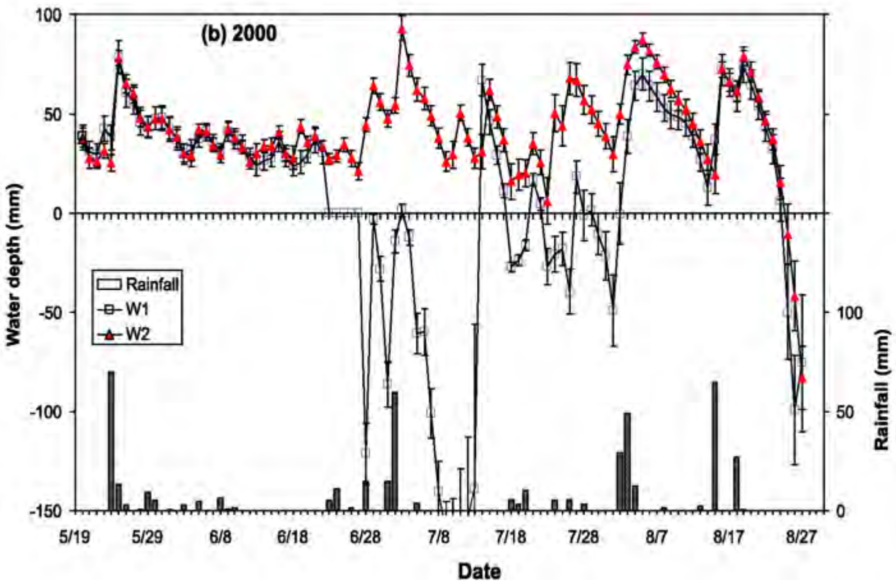


Figure 3. Mean ± SE (N=16, from four subplots and four replications) of water depths in alternate wetting and drying (W1) and continuous flooding (W2) in (a) 1999 all data (b) 1999 without W Rep1(c) 2000 all data and (d) 2000 without W1 Rep1. Tuanlin, Hubei Province, P. R. China.





Grain Yield

Average grain yield ranged from 3.2 to 5.8 t ha^{-1} in Jinhua (figures 4a–d), while higher grain yields of 4.4 to 9.2 t ha^{-1} were obtained in TL (figures 5a–b). Large variation in grain yield within each site was mainly due to yield responses to different treatments. The higher yield in TL was attributed to its longer crop duration compared with Jinhua. On average, grain yield in 2000 was higher than in 1999 in both sites, in accordance with the higher solar radiation in 2000 (table 2).

With regard to grain yield, W x N interaction was not observed in Jinhua in all seasons. In TL, W x N interaction was observed only in the 1999 experiment (tables 3 and 4). In both sites, the fertilizer effect was consistently significant in all seasons. The effect was mainly attributed to the significantly lower yield of the control compared with other fertilized treatments (figures 4 and 5). Among fertilizer splits in Jinhua, F_2 yielded higher than F_1 for most of the time but the difference was significant only in the continuous flooding of the early rice in 2000 (figure 4c). In TL (1999), F_1 gave the lowest yield in AWD but the highest in continuous flooding (figure 5a). In the rice crop of the same site in 2000, there were no observed significant differences among fertilizer split applications (figure 5b).

Figure 4. Effect of water and timing of fertilizer application on grain yield. Jinhua, Zhejiang, P. R. China. In the same water treatment, columns with the same letters (a, b, c) are not significantly different at 5 percent level.

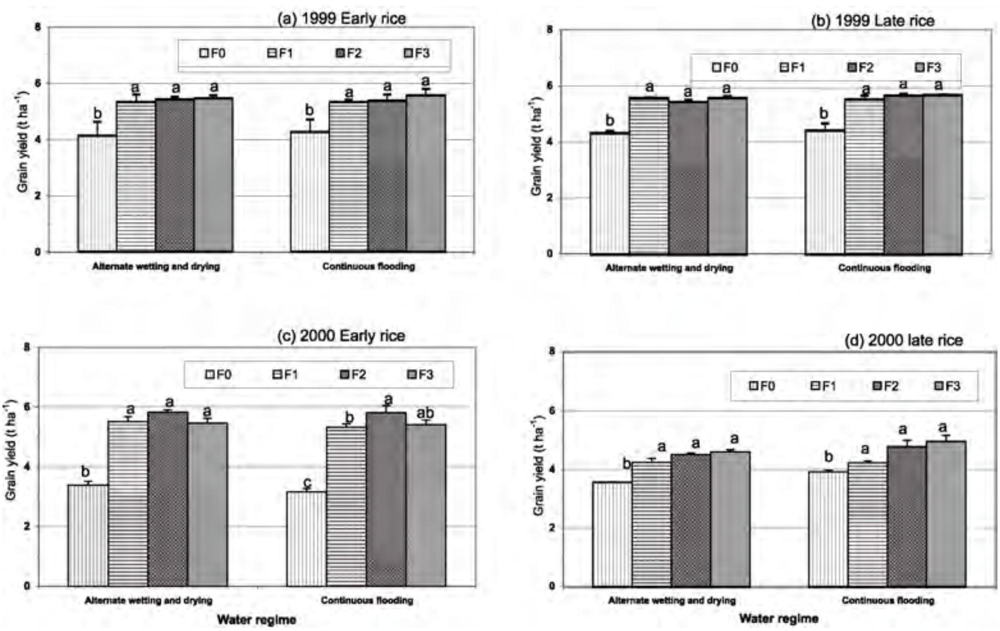
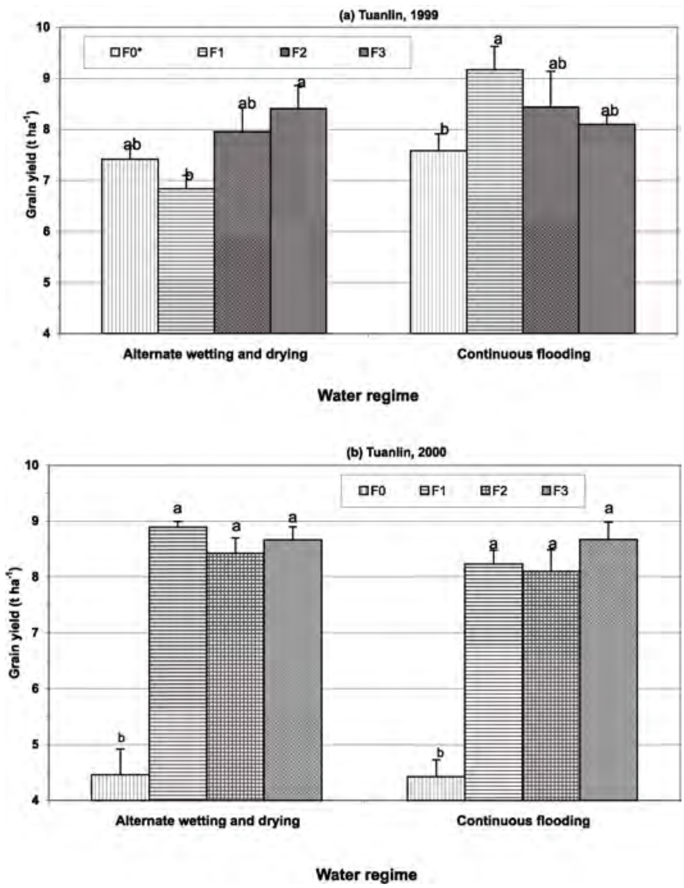


Figure 5. Effect of water and timing of fertilizer application on grain yield. (a) Jinhua, Zhejiang and (b) Tuanlin, Hubei, P. R. China. In the same water treatment, columns with the same letters (a, b, c) are not significantly different at 5 percent level.



The difference in grain yield between W_1 and W_2 ranged from 1 to 22%, depending on fertilizer splits and seasons (figures 4 and 5). In most cases, continuous flooding was higher than AWD except for the early rice season in Jinhua in 2000 and the experiment in TL in 2000 where grain yields were higher in the AWD irrigation treatments than in continuously flooded treatments.

Total Dry Matter

The total dry matter production ranged from 4.9 to 9.1 t ha^{-1} in Jinhua (figures 6a to d) and 8.5 to 18.1 t ha^{-1} (figures 7a and b) in TL. The large difference in total dry matter between Jinhua and TL and the variability within a site were due to the same reasons as for the difference in grain yield discussed earlier.

Figure 6. Effect of water and timing of fertilizer application on total dry matter rice, Jinhua, Zhejiang, P. R. China. In the same water treatment, columns with the same letters (a, b, c) are not significantly different at 5 percent level.

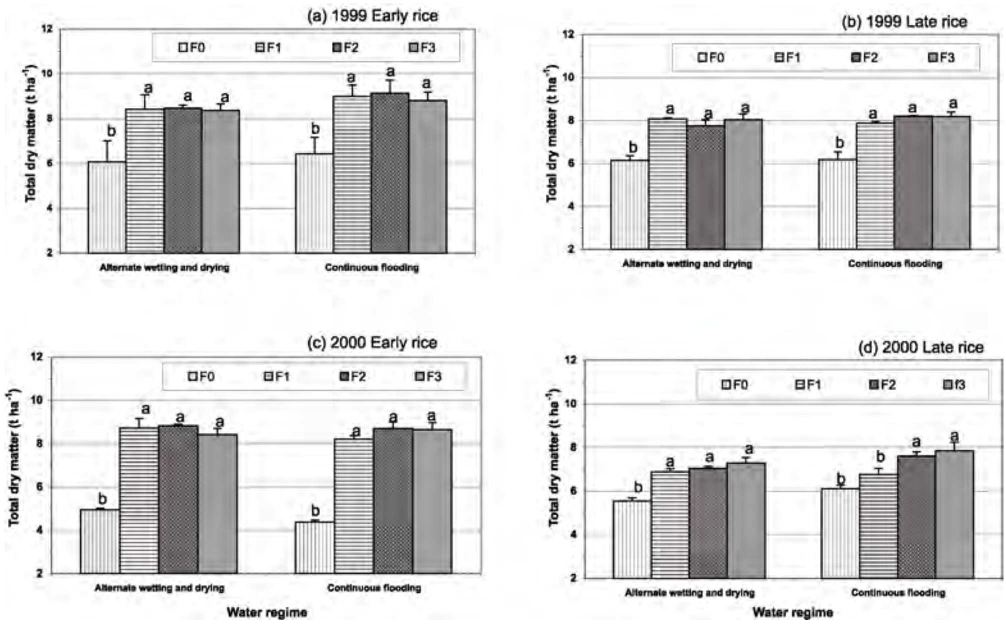
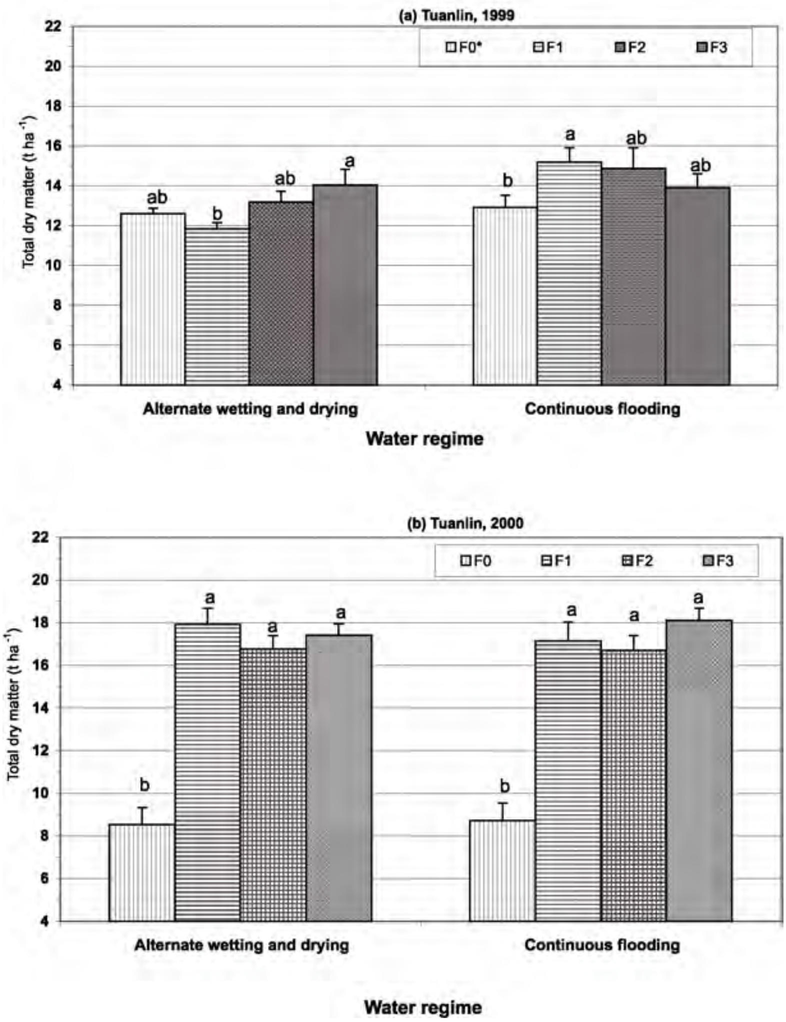


Figure 7. Effects of water and timing of fertilizer application on total dry matter. (a) Jinhua, Zhejiang and (b) Tuanlin, Hubei, P. R. China. In the same water treatment, columns with the same letters (a, b, c) are not significantly different at 5 percent level.



There was no observed W x N interaction in the total dry matter (table 3) in both sites. As in grain yield, the fertilizer effect was consistently significant when the control was compared with the mean of fertilizer split N treatments. There was no significant difference in the total dry matter production among F_1, F_2 and F_3 treatments in three out of four seasons in Jinhua (1999 and early rice of 2000) and in both years in TL. In late rice in Jinhua in 2000, however, a significant increase in the total dry matter was observed (figure 6d) in both F_2 and F_3 compared to the farmers' practice of 2-split application.

Table 3. Variability of grain, straw, total dry matter and N uptake as affected by water and timing of fertilizer, Jinhua and TL, 1999–2000.

Factor	Grain yield	Straw yield	Biomass	Total N uptake
		Early rice, Jinhua, 1999		
Water regime	ns	ns	ns	ns
Fertilizer	**	**	**	**
Among F_1, F_2, F_3	ns	ns	ns	**
F_0 v among F_1, F_2, F_3	**	**	**	**
W x N	ns	ns	ns	ns
		Late rice, Jinhua, 1999		
Water regime	ns	ns	**	ns
Fertilizer	**	**	ns	*
Among F_1, F_2, F_3	ns	ns	ns	**
F_0 v among F_1, F_2, F_3	**	**	**	**
W x N	ns	ns	ns	ns
		Early rice, Jinhua, 2000		
Water regime	ns	ns	ns	ns
Fertilizer	**	**	ns	**
Among F_1, F_2, F_3	*	ns	ns	**
F_0 v among F_1, F_2, F_3	**	**	**	**
W x N	ns	ns	ns	*
		Late rice, Jinhua, 2000		
Water regime	ns	ns	*	ns
Fertilizer	ns	**	*	ns
Among F_1, F_2, F_3	**	**	ns	*
F_0 v among F_1, F_2, F_3	*	**	-	-
W x N	ns	ns	ns	ns
		Rice season, TL, 1999		
Water regime	ns	ns	ns	ns
Fertilizer	ns	ns	ns	*
Among F_1, F_2, F_3	ns	ns	ns	ns
F_0 v among F_1, F_2, F_3	*	ns	ns	*
W x N	*	ns	ns	ns
		Rice season, TL, 2000		
Water regime	ns	ns	ns	ns
Fertilizer	**	**	**	**
Among F_1, F_2, F_3	**	**	**	**
F_0 v among F_1, F_2, F_3	ns	ns	ns	ns
W x N	ns	ns	ns	ns

Note: ns = not significant; * = significant at 5% level; ** = significant at 1% level.

Higher dry matter (about 2–7%) was observed in continuous flooding than in AWD (figure 6) in Jinhua. In TL, the differences in the total dry matter between W_1 and W_2 in 1999 was 1–22% with consistently higher values in continuously flooded than in AWD treatments, while in 2000, the difference between W_1 and W_2 was small (0.3–5%) and the trend was not consistent among fertilizer treatments (figure 7). In general, the differences due to water treatment in both sites were not statistically significant at 5% level except for the significantly higher total dry matter in F_1 of the continuous flooding treatment in TL compared to AWD in 1999.

Nitrogen Uptake

Nitrogen uptake ranged from 43 to 115 kg N ha^{-1} in Jinhua (figures 8a–d) and 62 to 195 kg ha^{-1} in TL (figures 9a and b). The N uptake tends to increase with the frequency of split applications of N fertilizer. Among the seasons in Jinhua, the average N uptake was highest in 1999, and the lowest was observed in the early rice season in 2000. The low N uptake in the early rice in 2000 was a combination of the lower N concentration in the grain and the low straw N concentration during the early rice seasons (data not shown). In TL, a higher uptake was observed in 2000 than in 1999 in agreement with the higher biomass in 2000.

Figure 8. Effect of water and timing of fertilizer application on total N-uptake. Jinhua, Zhejiang, P. R. China. In the same water treatment, columns with the same letters (a, b, c) are not significantly different at 5 paercent level.

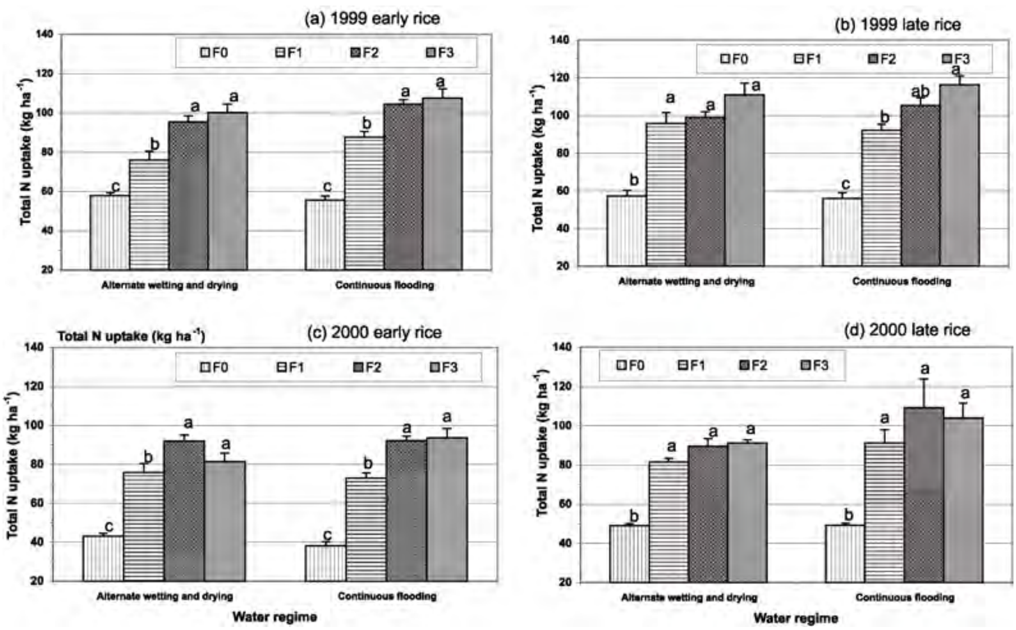
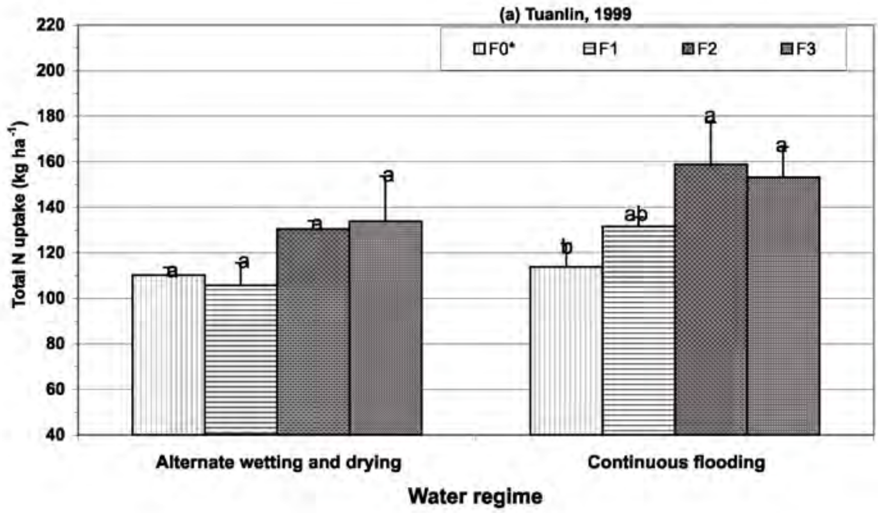
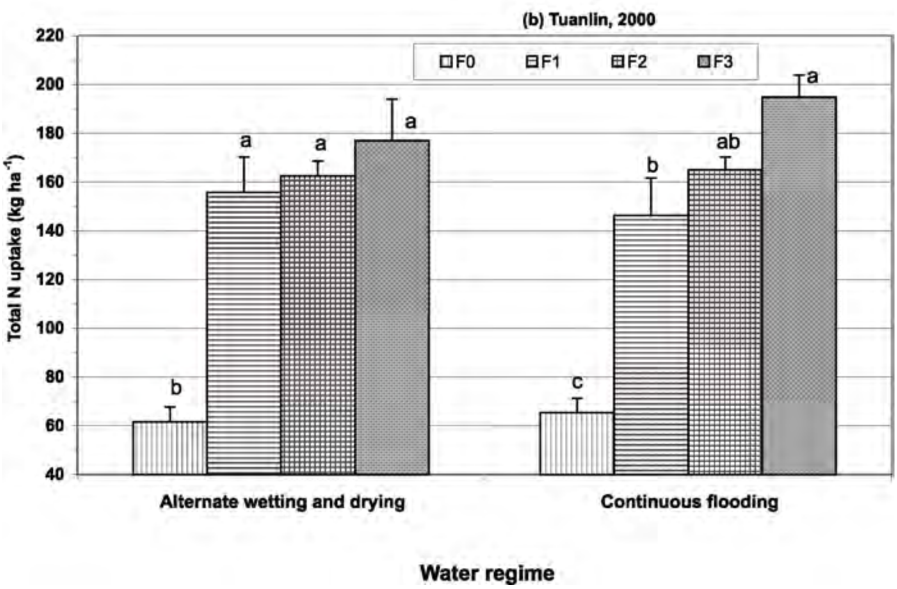


Figure 9. Effect of water and timing of fertilizer application on total N uptake (a) Jinhua, Zhejiang and (b) Tuanlin, Hubei, P. R. China. In the same water treatment, columns with the same letters (a, b, c) are not significantly different at 5 percent level.





As in the agronomic parameters, there was no observed W x N interaction on N uptake in crops in 1999 and late rice in Jinhua in 2000 and in both years in TL (table 3). In Jinhua, there was however a significant water-nitrogen interaction with N uptake in early rice in 2000. The fertilizer effect was consistently significant in both years when the basal and control treatments were compared with the mean of fertilizer split N treatments. Among fertilizer splits, the N uptake in farmers' practice of two splits was consistently lower than the N uptake of F_2, and F_3 in Jinhua but the difference was only significant in the early rice crop. Higher uptakes in F_2 and F_3 in both sites were mainly due to a higher N concentration in both grain and straw (data not shown).

At both sites, the difference in N uptake between W_1 and W_2 ranged from 0.2 to 20% depending on the number of fertilizer splits. In most cases, N uptake in the continuously flooded treatment was higher than in the AWD treatment. However, all differences were not significant at 5% level.

Nitrogen Use Efficiency

There was no observed W x N interaction in all N-use efficiency parameters in all seasons in Jinhua and TL (table 4). As in the agronomic parameters, the fertilizer effect was consistently significant when the control was compared with the mean of fertilizer split N treatments. In TL, however, ANUE and AR were not computed in 1999 since the experiment did not include 0-N treatment. The fertilizer effect was not observed in 1999, but it was significant in 2000.

Table 4. Variability of different N-use efficiency parameters as affected by water and timing of fertilizer application, Jinhua and TL, 1999–2000.

Factor	NHI[α]	PNUE[β]	ANUE[χ]	AR[ϕ]
		Early rice, Jinhua, 1999		
Water regime	*	ns	ns	**
Fertilizer	**	**	ns	**
Among F_1, F_2, F_3	ns	**	-	-
F_0 v among F_1, F_2, F_3	**	**	-	-
W x N	ns	ns	ns	ns
		Late rice, Jinhua, 1999		
Water regime	ns	ns	ns	ns
Fertilizer	**	**	ns	*
Among F_1, F_2, F_3	ns	*	-	-
F_0 v among F_1, F_2, F_3	**	**	-	-
W x N	ns	ns	ns	ns
		Early rice, Jinhua, 2000		
Water regime	ns	ns	ns	ns
Fertilizer	ns	**	ns	**
Among F_1, F_2, F_3	ns	*	-	-
F_0 v among F_1, F_2, F_3	ns	**	-	-
W x N	ns	ns	ns	ns
		Late rice, Jinhua, 2000		
Water regime	ns	ns	*	ns
Fertilizer	ns	**	*	ns
Among F_1, F_2, F_3	ns	ns	-	-
F_0 v among F_1, F_2, F_3	*	**	-	-
W x N	ns	ns	ns	ns
		Rice season, TL, 1999		
Water regime	ns	ns		
Fertilizer	ns	ns		
Among F_1, F_2, F_3	ns	ns		
F_0 v among F_1, F_2, F_3	ns	ns		
W x N	ns	ns		
		Rice season, TL, 2000		
Water regime	ns	ns	ns	ns
Fertilizer	ns	**	ns	*
Among F_1, F_2, F_3	ns	*	-	-
F_0 v among F_1, F_2, F_3	ns	**	-	-
W x N	ns	ns	ns	ns

Note: ns = not significant; * = significant at 5% level; ** = significant at 1% level; αNitrogen Harvest Index (NHI) = (grain N uptake / total plant N uptake); βPhysiological N use efficiency (PNUE, kg grain/ kg N uptake) = {(grain yield *0.86) / total plant N uptake};χAgronomic N use efficiency (ANUE, kg grain/ kg N applied) = {(grain $yield_{fertilized}$ – grain $yield_{control}$) * 0.86} / fertilizer N applied; ϕApparent recovery of applied N (AR, %) = (total N $uptake_{fertilizer}$ – total N $uptake_{control}$) / fertilizer N applied * 100

NHI in fertilizer treatments did not vary greatly in all seasons, ranging from 0.56 to 0.76 (table 5 and 6). The relatively high NHI values were probably due to high grain yields and high grain N concentrations (data not shown). The highest NHI was observed in the control treatment. NHI values tended to decline with increasing number of fertilizer split applications, though the level of significance was not consistent among seasons. The relatively high NHI values were probably due to high grain N concentration (data not shown).

Table 5. Nitrogen efficiency parameters as affected by water and timing of fertilizer application, Jinhua, 1999–2000.

Treatment	NHI[α]	PNUE[β]	ANUE[χ]	AR[ϕ]	NHI[α]	PNUE[β]	ANUE[χ]	AR[ϕ]
AWD irrigation	Early rice, 1999				Late rice, 1999			
F_O	0.76 a	61 a	-	-	0.68 a	66 a	-	-
F_1	0.69 ab	61 a	7 a	12 b	0.62 b	50 b	7 a	26 a
F_2	0.66 b	49 b	7 a	25 a	0.66 ab	47 b	6 a	28 a
F_3	0.65 b	47 b	7 a	28 a	0.65 ab	44 b	7 a	36 a
Continuous flooding								
F_O	0.72 a	66 a	-	-	0.73 a	68 a	-	-
F_1	0.61 b	52 b	6 a	21 b	0.66 b	52 b	6 a	24 b
F_2	0.64 ab	45 b	6 a	33 a	0.67 b	47 bc	7 a	33 ab
F_3	0.64 b	44 b	8 a	35 a	0.64 b	42 c	7 a	40 a
AWD irrigation	Early rice, 2000				Late rice, 2000			
F_O	0.65 a	68 a	-	-	0.69 a	63 a	-	-
F_1	0.63 a	63 ab	13 a	22 b	0.60 a	45 b	4 a	22 a
F_2	0.63 a	55 b	14 a	33 a	0.62 a	43 b	6 a	27 a
F_3	0.61 a	58 ab	12 a	25 b	0.65 a	43 b	6 a	28 a
Continuous flooding								
F_O	0.68 a	72 a	-	-	0.70 a	69 a	-	-
F_1	0.65 ab	63 ab	13 a	23 b	0.62 a	40 b	2 b	28 a
F_2	0.67 ab	54 bc	15 a	36 a	0.66 a	39 b	5 a	40 a
F_3	0.58 b	50 c	13 a	37 a	0.62 a	41 b	6 a	37 a

In a column for each season and water regime, means followed by a common letter are not significantly different at 5% level by DMRT; αNitrogen Harvest Index (NHI) = (grain N uptake / total plant N uptake); βPhysiological N use efficiency (PNUE, kg grain/kg N uptake) = {(grain yield * 0.86) / total plant N uptake}; χAgronomic N use efficiency (ANUE, kg grain/kg N applied) = {(grain $yield_{fertilized}$ – grain $yield_{control}$) * 0.86} / fertilizer N applied; ϕApparent recovery of applied N (AR, %) = {(total N $uptake_{fertilized}$ – total N $uptake_{control}$) / fertilizer N applied} * 100.

Table 6. Nitrogen efficiency parameters as affected by water and timing of fertilizer application, Tuanlin, 1999–2000.

Treatment	NHI[α]	PNUE[β]	ANUE[χ]	AR[ϕ]
AWD irrigation	**Rice season, 1999**			
F_0	0.71 a	61 a		
F_1	0.69 a	61 a		
F_2	0.70 a	49 b		
F_3	0.64 a	47 b		
Continuous flooding				
F_0	0.69 a	66 a		
F_1	0.72 a	52 b		
F_2	0.63 a	45 b		
F_3	0.67 a	44 b		
AWD irrigation	**Rice season, 2000**			
F_0	0.67 a	62 a	-	-
F_1	0.60 a	50 b	21 a	52 a
F_2	0.60 a	45 b	19 a	56 a
F_3	0.58 a	43 b	20 a	64 a
Continuous flooding				
F_0	0.63 a	59 a	-	-
F_1	0.57 a	50 b	18 a	45 b
F_2	0.56 a	43 bc	18 a	55 ab
F_3	0.67 a	39 c	20 a	72 a

In a column for each season and water regime, means followed by a common letter are not significantly different at 5% level by DMRT; aNitrogen Harvest Index (NHI) = (grain N uptake / total plant N uptake); bPhysiological N use efficiency (PNUE, kg grain/ kg N uptake) = {(grain yield * 0.86) / total plant N uptake}; cAgronomic N use efficiency (ANUE, kg grain/kg N applied) = {(grain $yield_{fertilized}$ – grain $yield_{control}$) * 0.8 6} / fertilizer N applied; fApparent recovery of applied N (AR, %) = {(total N $uptake_{fertilized}$ – total N $uptake_{control}$) / fertilizer N applied} * 100.

PNUE values ranged from 39 to 72 kg grain/kg N uptake with decreasing values as the number of splits increased (tables 5 and 6). PNUE values tend to decrease with increasing N splits. This was reflected in the higher N concentrations in both the grain and straw (data not shown) in F_2 and F_3 compared with F_0 and F_1.

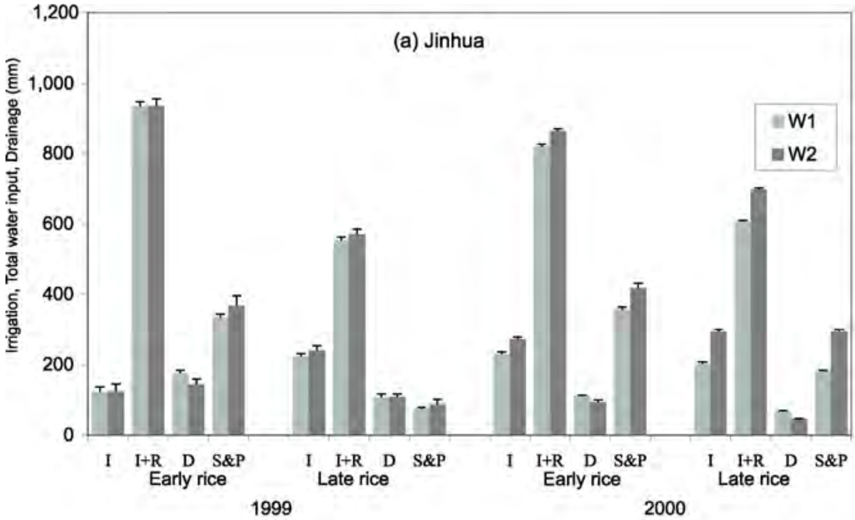
ANUE values ranged from 2 to 15 kg grain/kg N applied (table 5) in Jinhua and from 18 to 21 kg grain/kg N applied in TL (data available only for year 2000) (table 6). ANUE values in F2, F3 and F1 were comparable.

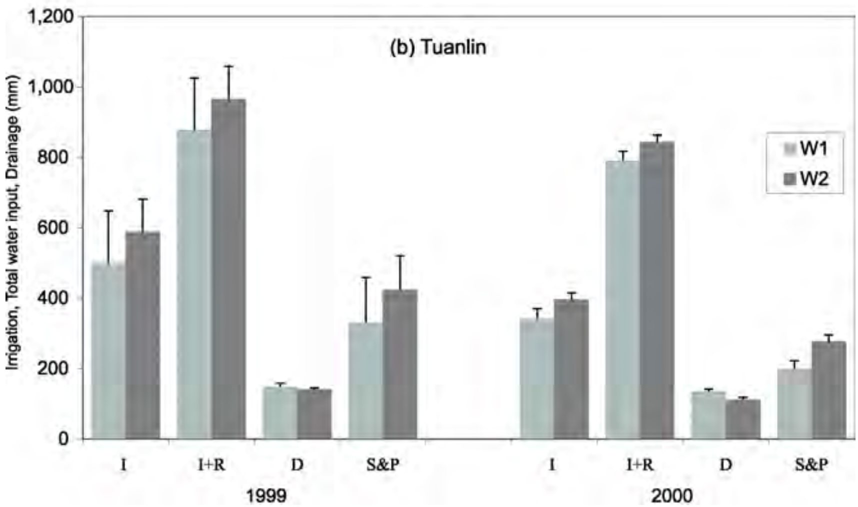
Values of AR ranged from 12 to 40% in Jinhua (table 5) and 45 to 72% in TL (only in year 2000) (table 6). The increase in AR in F_2 and F_3 conforms to the increase in N uptake with the increasing number of splits. ANUE and AR values in TL were higher than in Jinhua. This was because the difference between the zero N and other N treatments was higher in TL (about 4 t ha^{-1}) than in Jinhua (about 3 t ha^{-1}).

Drainage, Seepage and Percolation

The amount of drainage water was higher in W_1 than W_2, significant at 5% level in both sites in 2000 and in the early rice of 1999 (figure 10). The higher drainage water observed in W_1 was because water was deliberately drained to realize the periodic drying, especially in the long drying period (mid-season drainage) at the tillering stage.

Figure 10. Water balance components in alternate wetting and drying (w_1) and continuous flooding (w_2) in 1999 and 2000 in (a) Jinhua, Zhejiang Province and (b) Tuanlin, Hubei Province, P. R. China.





In TL, the daily seepage and percolation rates in replication 1 of treatment W_1 was exceedingly higher (>20 mm day^{-1}) than in other replications (<6 mm day^{-1}). This was because there was a drainage pipe network previously installed in replication 1 of treatment W_1. This replication was removed for our subsequent analysis of water balance and water productivity. The mean seepage and percolation rate for other replications was 4–6 mm day^{-1} in 1999 and 3 mm day^{-1} in 2000. The lower seepage and percolation rates in 2000 could be attributed to the construction of cement linings along the main plots in 2000.

The mean seepage and percolation rate in Jinhua was 3.8 mm day^{-1}, varying from 1 to 6 mm day^{-1}. At both sites, there was no significant difference in seepage and percolation rates between the two water treatments. Over the crop season, the total amount of seepage and percolation was consistently higher in W_2 than in W_1 at both sites, but the differences were significant only in 2000 (figure 10). Since there were no significant differences in S&P rates between W_1 and W_2, the higher amount of total seepage and percolation in W_2 can be attributed to the greater number of days with standing water in W_2.

Water Input

In Jinhua, the total water input (rainfall + irrigation) ranged from 554 to 934 mm per crop. The total water input in early rice crops was invariably higher than in the late rice crops (figure 10). This was due to the higher rainfall in the early rice crop. Irrigation water in the late season crop of 1999 (about 230 mm) was much higher than the early season crop of 1999 (about 120 mm). This conforms to the higher rainfall in the early rice season in 2000. Despite the high rainfall in the early rice crop of 2000, the amount of irrigation water was comparable to that in the late rice crop. This was due to the high evaporative demand in the season (table 2). In TL, the total water input ranged from 732 to 1,144 mm. The total water input in 1999 (930 mm) was higher than in 2000 (820 mm) (figure 10). This was due to the lower rainfall in 1999 (table 2).

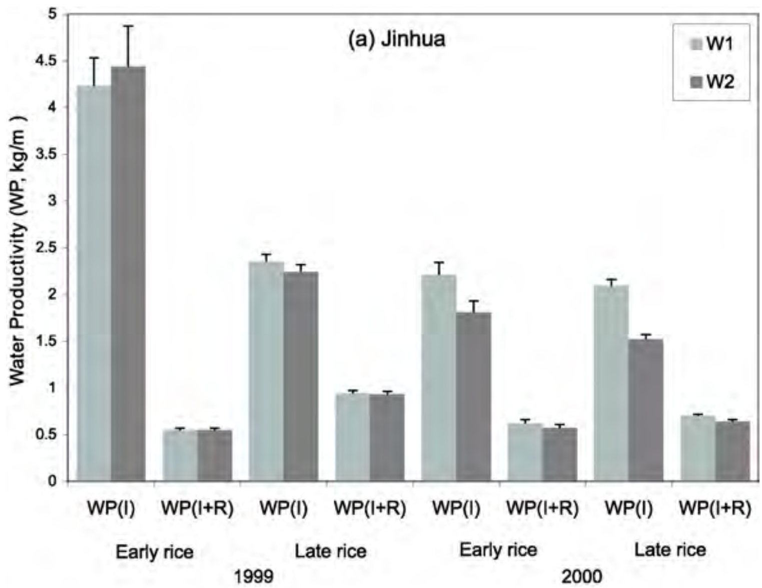
In most cases, irrigation under continuous flooding treatment was higher than under AWD but the differences were statistically significant only in the year 2000, when larger irrigation amounts were required. The largest difference in irrigation water between the two water treatments occurred in Jinhua in the late rice season of 2000.

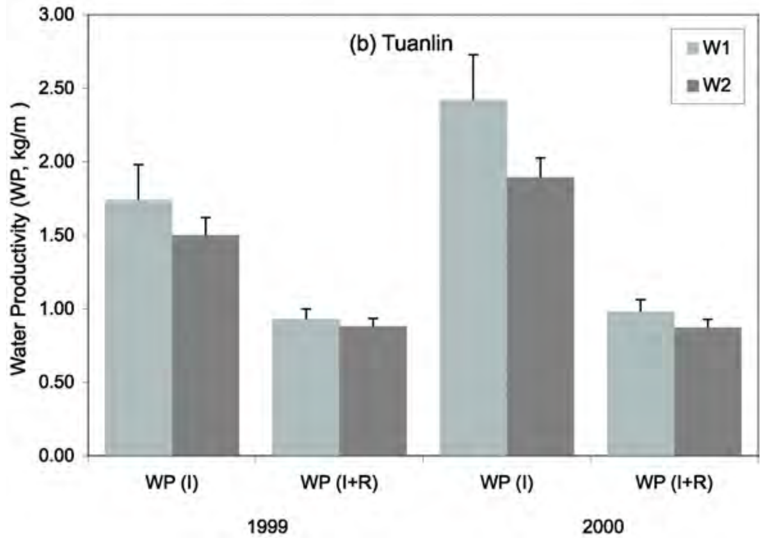
Water Productivity

Water productivity in terms of total water input (irrigation + rainfall, WP_{IR}) ranged from 0.55 to 0.94 kg m^3 in Jinhua, and from 0.87 to 0.98 kg m^3 in TL (figure 11). In both sites, WP_{IR} was generally higher in W_1 than in W_2 but the difference was statistically significant in Jinhua, only in the late rice season of 2000 (figure 11).

Water productivity in terms of irrigation (WP_I) ranged from 2.1 to 4.2 kg m^3 in Jinhua, and from 1.50 to 2.42 kg m^3 in TL. WP_I in Jinhua was higher in the early rice crop than in the late rice crop because of lower irrigation water input in the early rice. As in TL, WP_I was higher in 2000 than in 1999, due to the lower irrigation water input in 2000. WP_I was higher under AWD than under continuous flooding in three out of four seasons in Jinhua (except for the early rice crop of 1999), and in both years in TL. In these cases, the increase in WP_1 was mainly due to the lower irrigation water input in W_1 (figure 10). For the early rice crop of 1999, WP_1 under continuous flooding was slightly higher than that under AWD because the amount of irrigation was similar in both treatments while the yield under continuous treatment was slightly higher than under AWD.

Figure 11. Water productivities with respect to irrigation (WPI) and to the total water input ($WP_{(1+R)}$) in alternate wetting and drying (W_1) and continuous flooding (w_2) in 1999 and 2000 in (a) Jinhua, Zhejiang Province, and (b) Tuanlin, Hubei Province, P. R. China.





Conclusions

Increasing the number of splits increased the total N uptake, but not the grain yield and biomass compared to farmers' practices of two splits. In most cases, continuous flooding gave 1–25% higher yields than AWD, though there are cases where AWD gave higher yields. However, the yield differences were not statistically significant at 5% level. Our study showed that periodic drying of the soil was not a prerequisite for high yield. There was no significant water-nutrient interaction on grain yield, biomass and N uptake. Thus, AWD does not require N-fertilizer management differently from continuous flooding

In our study, AWD reduced irrigation only by a small amount if measured in absolute terms (maximum 90 mm in Jinhua, maximum 80 mm in TL) compared to continuous flooding. But this saving accounted up to 30% of the irrigation water. This is because the study sites had relatively high rainfall, low percolation and seepage and, therefore, a low total of irrigation water. Nevertheless, AWD could raise the water productivity with respect to irrigation water by about 5–35% compared to continuous flooding in Jinhua, and by 16–28% in TL. The amount of water saved and the increase in water productivity will probably become more important in more-pronounced dry conditions or in more-permeable soils. Farmers can also reduce the amount of irrigation further by not having to drain the field to achieve periodic drying. AWD can thus be an important technology for farmers to cope with water scarcity and may help increase water productivity at the regional scale if on-farm water saved can be used more productively downstream.

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Chapter 5

Comparative Assessment of On-farm Water-Saving Irrigation Techniques in the Zhanghe Irrigation System

P. Moya, L. Hong, D. Dawe and C. D. Chen[1]

Abstract

Introduction

The *alternate wetting and drying* (AWD) irrigation technique has been introduced to farmers to save water, in the belief that it will increase yield. However, the adoption of AWD among the farmers was slow because of traditional concepts and habits, a high risk of lodging with AWD and lack of training and guidance (Dong and Loeve 2000). In many areas of ZIS, farmers still practice *continuous water application*.

A comparative assessment was conducted of these two methods of on-farm water-management strategies for rice in two sites within the Zhanghe Irrigation System (ZIS). It was conducted during the wet season rice crops of 1999 and 2000. The objective was to evaluate the impact of AWD irrigation techniques on crop management and the profitability of rice production. The study also investigated whether farmers in sites where AWD techniques were introduced were knowledgeable about them and were actually practicing it. The townships of Tuanlin (TL) and Wenjiaxiang (WJX) were selected for the study; TL represents the area where AWD techniques are supposed to be practiced by the farmers while WJX represents the site where these techniques are not being practiced. Detailed data regarding on-farm water-management strategies, such as frequency and timing of irrigation, depth of water applied, sources of water, pond and pump use, were collected from 30 sample farmers from each site through farmer interviews. Input and output data of rice production including prices were also collected to make an economic comparison of the two sites in terms of rice production and profitability.

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Site and Sample Description

Thirty sample farmers from the Shuangbei village near the TL Experimental Station were selected in the site where the AWD irrigation techniques are being practiced. The area is served by the first branch of the third main canal of ZIS. Similarly, 30 other sample farmers were selected from the Wanyan village at the Lengshui township where AWD is not practiced but where continuous irrigation is practiced. Lengshui is near the township of WJX where the fourth main canal is located and the east branch of this canal of ZIS irrigates this area. The elevation of farmers' fields vary and, therefore, the samples were selected in such a way that 10 farmers from each site had fields on a higher elevation, 10 on a medium elevation and 10 on a lower elevation. To be consistent with earlier reports we will use TL to refer to the site where AWD is practiced and WJX to refer to the site where AWD is not practiced .

The mean farm size of the samples from both sites ranged from 0.65 to 0.70 hectare (table 1). The sample farmers have more or less similar socioeconomic characteristics as shown by the similar magnitudes of their age, family size and level of education. On average, farmers from TL and WJX have annual incomes of about 8,800 yuan and 12,000 yuan, respectively.

Table 1. Basic farm and household characteristics of sample farmers, TL and WJX, ZIS, Hubei, China.

	TL	WJX
Number of sample		
1999	22	30
2000	30	30
Mean farm size		
1999	0.66	0.68
2000	0.70	0.65
Mean household size	4.2	4.3
Mean age of farmer	40.8	40.7
Mean education of the farmer	9.1	9.4
Sources of household income (%)		
Rice crop	48	36
Non-rice crop	18	3
Livestock and poultry	11	11
Income from labor	0	0
Other sources	23	50
Total household income (yuan)	8,810	12,078

US$1.00=Yuan 8.27 in 2000.

On-Farm Water Management Practices of Farmers in TL and WJX

Many farms in the study sites are located at a higher altitude than the irrigation canals so that a majority of the farmers in TL and WJX keep farm ponds or small reservoirs for storing rainfall and pumped water from the ZIS irrigation canals to be used for on-farm irrigation. Farmers use water from these ponds or small reservoirs in more than one-fourth of irrigation events at both sites (table 2).

Table 2. Comparative uses of ponds among rice farmers in the two sample sites, ZIS, China.

	TL (%)	WJX (%)
Frequency of use of ponds as a source of water per irrigation event	28	25
Ownership of ponds		
Individually owned	54	41
Farmer group	0	22
Other farmer	13	30
Village	33	7
Other uses of ponds		
Aside from irrigation		
Raising fish	42	41
Lotus	4	4

In seasons with less rain, like the 2000 wet season, 70 percent of farmers in TL and 63 percent in WJX experienced problems of inadequate water supply in the various stages of the rice production cycle (table 3.). But in a rainy season like the 1999 wet season, 45 percent and 53 percent of the farmers from TL and WJX, respectively, sustained excessive water problems in their fields. Hence, the two seasons when observations on AWD were made could bring about different water application behaviors by farmers, especially so because the two areas are supposedly practicing different techniques of water application. In the section that follows, the basic parameters—such as frequency, duration, and depth of water application—of on-farm water application of the two sites will be analyzed and compared.

Table 3. Number of farmers with water availability problems at different crop growth stages, TL and WJX, ZIS.

Crop stages	No water				With excess water			
	TL		WJX		TL		WJX	
	1999	2000	1999	2000	1999	2000	1999	2000
Land preparation	1	1	6	5		1	2	0
Transplanting	0	6	6	8		1	1	1
Vegetative	2	11	4	11	9	3	9	5
Reproductive	3	10	5	16	1	2	4	1
Total*	5	21	15	19	10	3	16	6
Percent of total sample	23	70	50	63	45	10	53	20

*Some farmers who had problems with two or more crop stages were counted once in the total.

Frequency and Depth of Irrigation Application

A summary of the frequency of irrigation (from land preparation to harvesting) of the farmers from the two sites showed that the number of irrigation application of farmers from TL is slightly lower than that from WJX for both seasons (table 4). However, the difference is not statistically significant. In the 1999 wet season, farmers from WJX irrigated their crops more frequently when there was still standing water in the soil (2.8 times) than when the soil was either saturated or dry. As expected, farmers from TL practiced the opposite strategy and more commonly applied water when the soil in the field was dry (2.6 times on average) than when it was either wet or had standing water. In the 2000 wet season, when there was little rain, farmers in both sites irrigated their fields more frequently under dry-soil conditions.

Table 4. Frequency of irrigation application according to soil condition immediately Before the irrigation event.[1]

	WS rice, 1999		WS rice, 2000	
Soil condition	TL	WJX	TL	WJX
With standing water	2.0	2.8	0.6	0.6
Saturated (wet)	1.1	1.3	2.5	2.6
Dry	2.6	2.2	2.8	3.2
Total number of irrigation applications	5.8	6.3	5.8	6.4

[1]Includes all irrigation applications from land preparation to harvesting.
Note: WS rice=Wet-season rice in this table and in others.

The amount of irrigation water applied varied by crop-growth stages and by sites in both the 1999 and 2000 wet seasons (table 5). The total seasonal water depth applied by farmers in WJX was 42 percent higher than that in TL during the 1999 wet season but it was only 3 percent higher in the 2000 wet season, a relatively dry year. During the crop-growth period, the total amount of water applied by WJX farmers was about 80 percent higher than that applied by TL farmers during the 1999 wet season but only 4 percent higher in the 2000 wet season. The result indicated that nearly all farmers practice a form of AWD when less water is available.

Table 5. Depth of standing water at the end of irrigation events by different crop stages, TL and WJX, ZIS, Hubei, China.

	WS rice, 1999		WS rice, 2000		Average	
	TL	WJX	TL	WJX	TL	WJX
Water applied by crop stage (mm)						
Land preparation	47	55	88	86	70	71
Transplanting	25	60*	38	40	32	50*
Crop growth	133	239*	266	277	210	258
Total depth	205	354*	392	403	312	379*

*Mean values are significantly higher than at TL.

AWD in Farmers' Fields

The alternate wetting and drying (AWD) system of irrigation for rice implies that rice fields are not kept continuously submerged but that they are allowed to dry intermittently beginning 30 days after transplanting. During this period, farmers adopting this system are expected to irrigate only when their fields are either saturated or dry. Thus, all irrigation events during land preparation, seedbed preparation and transplanting were not considered in our analysis of on-farm water-management practices. Table 6 shows the average number of irrigation applications during the crop-growth period that begins 30 days after transplanting. In 1999, farmers in TL allowed the soil to become dry before applying irrigation water more frequently than those in WJX, and the latter were more likely to irrigate when the fields were either saturated or with standing water. But, during dry periods as in 2000, the behavior of farmers at the two sites was quite similar. There was not much difference in the total number of irrigation applications between the two sites in either year.

Table 6. Average number of irrigation applications during the crop-growth period,[1] according to the soil-water condition immediately before the irrigation event, ZIS, Hubei, China.

Soil-water status	WS rice, 1999		WS rice, 2000	
	TL	WJX	TL	WJX
With standing water	0.75	0.81	0.0	0.19
Saturated (wet)	0.31	0.58	1.17	0.76
Dry	0.94	0.69	1.33	1.38
Total	2.0	2.08	2.5	2.33

[1]Includes all irrigation events on the 30th day or 30 days after transplanting.

Additional information collected from the survey reveals that not all farmers in TL where AWD was introduced have a knowledge of AWD techniques. Roughly 13 percent of our sample in TL said that they had no knowledge of AWD and were not practicing it. On the other hand, 43 percent of the sample from WJX was aware of AWD, and six of these farmers stated that they were practicing it (table 7). Only one farmer at WJX claimed to have undergone training in AWD techniques. No farmer in TL reported attending such training.

Table 7. Knowledge of AWD irrigation techniques among sample farmers, ZIS, Hubei, China.

Sites	No. of sample	With knowledge (%)	Without knowledge (%)	Adaptor
TL	30	26 (87)	4 (13)	25
WJX	30	13 (43)	17 (57)	6

AWD Scores

To compare individual farmer's irrigation strategies and to determine whether they are, in fact, practicing AWD or not, we established a scoring system, ranging from 0 to 1. The following equation was used in computing the AWD score of an irrigator:

$$AWD\ score = \frac{X \times 1 + Y \times 0.5 + Z \times 0}{X + Y + Z}$$

where,

X = number of times a farmer irrigates when the soil is dry,
Y = number of times a farmer irrigates when the soil is wet or saturated,
Z = number of times a farmer irrigates when the soil is with standing water, and
1, 0.5 and 0 are arbitrary weights assigned to dry, wet or saturated, and standing water conditions, respectively, at the time of water application.

Only irrigation events on the 30th day or 30 days after transplanting of the crop and until the crop was harvested were considered in computing the AWD score. On an individual farmer basis, if all his or her irrigation application happened only when the soil was dry then a farmer gets a score of 1. A score of 0 results if all his or her irrigation applications happened when there was still standing water in the soil, and the AWD score is between 0 and 1 if a farmer had irrigated at a combination of different soil-water statuses. The score then will indicate if the farmer tends to practice AWD or not, with higher scores indicating a greater adoption of AWD.

Farmer AWD Irrigation System

Figure 1a shows a scatter plot of the AWD score of the farmers from two different water distribution schemes, in the 1999 wet season. Many farmers from WJX always kept the soil submerged during the crop-growth period as shown by their score of 0. Surprisingly, there were also some farmers in TL who did the same.

In contrast to 1999, the rice crop in the year 2000 was quite different in terms of AWD score patterns (figure 1b). All farmers except one got an AWD score of 0.5 or higher and 16 got 1 indicating that in 2000 (a dry year) the majority of farmers tended to practice the AWD system of irrigation regardless of whether they belonged to a site where AWD had been introduced. In 1999, the mean AWD scores of all farmers in TL and WJX were 0.58 and 0.42, respectively, but in 2000 their scores were almost equal, about 0.8 (table 8).

In general, AWD scores were higher for farmers who claimed to practice AWD, as would be expected. The AWD scores indicate that most farmers did not practice a pure form of either AWD or continuous flooding.

Figure 1a. Alternate wet dry scores, 1999 WS rice, ZIS, China.

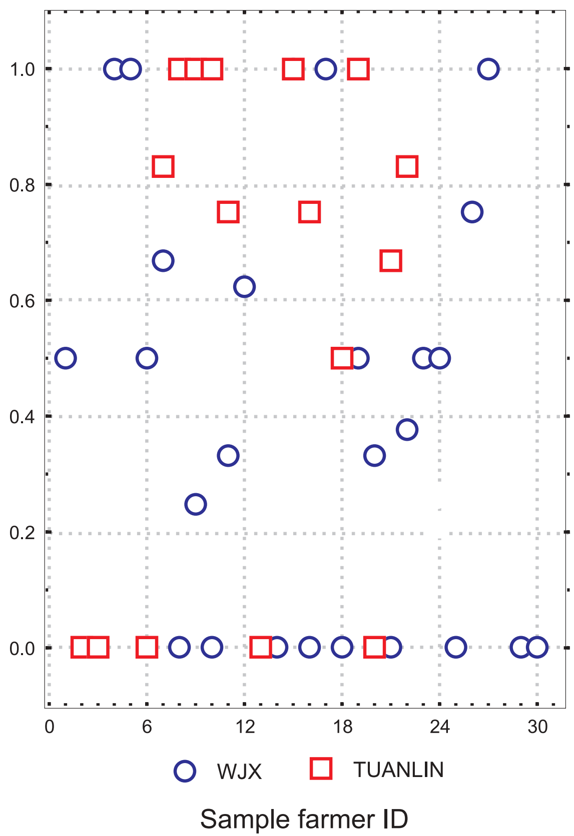


Figure 1b. Alternate wet dry scores, 2000 WS rice, ZIS, China.

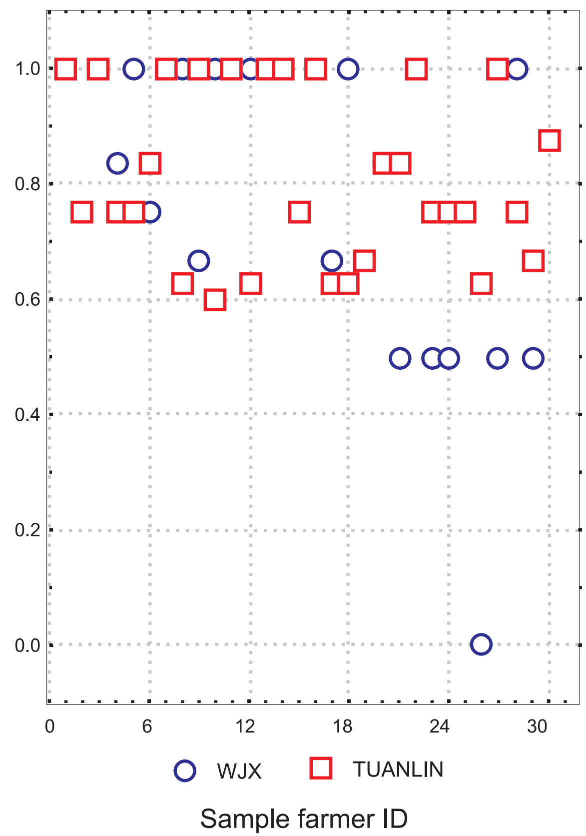


Table 8. Comparative AWD scores of farmers stratified by site, year, and reported practice of AWD.

	AWD	Non-AWD	All	Both years
TL				
1999	0.58	0.61	0.58	0.73
2000	0.80	0.92	0.82	
WJX				
1999	0.51	0.39	0.42	0.58
2000	0.88	0.74	0.78	
Both sites and years	0.72	0.59		

AWD and Input Use

A comparison of raw material input use by farmers showed that, on average, the WJX farmers applied more nitrogen fertilizer and organic manure to the rice crop than the TL farmers, and spent more money on pesticides (table 9). On the other hand, the TL farmers used more seeds per hectare (the WJX farmers used hybrid rice more frequently than the TL farmers) and applied more potassium than the WJX farmers.

In general, WJX farmers used much more labor for rice production than the TL farmers. On average, total labor use of WJX farmers was about 145 person-days compared to only 91 person-days in TL (table 10). This difference may be due to thorough land preparation, additional canal maintenance, a different method of transplanting the crop, and higher yield (which requires more labor for threshing and harvesting).

Table 9. Comparative yield and input use, irrigated WS rice, TL and WJX, ZIS, Hubei, China.

	WS rice 1999		WS rice 2000		Average	
	TL	WJX	TL	WJX	TL	WJX
Yield per hectare (tons/ha)	7.82	8.53*	6.66	7.84*	7.15	8.18*
Fertilizer use (kg/ha)						
Nitrogen	153	165	160	208*	157	187*
Phosphorus	44	43	44	51*	44	47
Potassium	7	0	36	3	24*	1.5*
Seed use (kg/ha)	26*	20	30*	22	28*	21
Manure (t/ha)						
Pesticide use (yuan/ha)	3.2	4.8	1.1	5.0*	2.0	4.9*
Insecticide	114	124	72	92	90	108
Herbicide	36	59*	25	44*	29	52*

*Mean values are significantly higher than at the others site at the 5 percent level.

Table 10. Labor use for wet-season rice production, TL and WJX, ZIS, China, 1999–2000.

	WS rice 1999		WS rice 2000		Average	
	TL	WJX	TL	WJX	TL	WJX
	(Person-days per hectare)					
Land preparation	8	10	8	21*	8	15*
Crop establishment	19	23	30	55*	25	39*
Crop care	18	29*	15	45*	16	37*
Hand weeding	4*	2	2	1	3*	1
Irrigation labor	8	16*	6	30*	7	23*
Harvesting and threshing	37	48	46	59*	42	54*
Total labor use	82	110*	98	181*	91	145*
Family labor	72	105*	87	174*	81	139*
Hired labor	11	5	11	7	11*	6

*Mean values are significantly higher than at the other site at the 5 percent level.

Excluding labor for canal maintenance, the value of 11.2 person-days per hectare spent for actual irrigation of the rice field by WJX farmers is significantly higher than the value of 6 person-days/ha spent by TL farmers. This may be due to the larger number of irrigation applications and more water applied per irrigation.

It is a general belief that continuous submergence of rice fields is often practiced by farmers to control weeds, thus reducing labor for weeding or minimizing the use of herbicides. With the adoption of AWD techniques, farmers might be expected to control weeds either through more intensive hand weeding or through the application of additional herbicides. In TL, where AWD is more common, farmers spent more labor for hand weeding than WJX farmers in both years. However, the amount of labor spent for this particular activity was smaller in magnitude than that spent for other rice production activities.

To further determine if AWD is correlated with herbicide use, hand weeding or nitrogen fertilizer, we regressed the quantity of each of these inputs against AWD scores, site and year dummies, and interactions of AWD scores with the dummy variables. The coefficients of the AWD score and its interactions were not significant in any of the regressions (table 11). Thus, there appears to be little effect of AWD on input use.

Table 11. Regression estimates of the models used in relating AWD scores to input use, wet season rice 1999–2000, ZIS, Hubei, China.

Parameters	Model 1 (NHA)		Model 2 (HW lab)		Model 3 (Herb cost)	
	Coefficient estimate	Standard error	Coefficient estimate	Standard error	Coefficient estimate	Standard error
Intercept	179.2	37.2	1.84	1.87	48.4	14.2
AWD score	25.1	45.6	-1.62	2.16	0.3	17.4
Site dummy 1=TL 0= WJX	-9.6	30.0	2.72	1.43	-8.4	11.7
Year dummy 1=1999 0=2000	-11.2	39.1	-0.34	1.85	2.8	14.9
AWD score* site dummy	-30.5	39.8	-0.39	1.90	-20.4	15.1
AWD score* year dummy	-21.6	49.9	3.33	2.36	5.2	19.2
Herbicide cost			-0.01	0.01		
Hand-weeding labor					-0.7	0.9
Adjusted R^2	0.04		0.19		0.22	
R^2	0.08		0.24		0.27	

Model 1 - N fertilizer use at kg/ha as dependent variable.
Model 2 - Hand weeding labor (person-days/ha) as dependent variable.
Model 3 - Herbicide cost (yuan/ha) as dependent variable.

Effect of AWD on Yield

There are no data yet at the farm level to show that farmers adopting the AWD irrigation produced a significantly higher yield than those using other irrigation strategies.

Mean rice yields at WJX were significantly higher than those at TL in both years. The average yield of WJX for the two wet seasons was 8.18 tons per hectare compared to only 7.15 tons per ha for TL (table 9).

Although farmers at TL are more likely to use AWD strategies, it does not necessarily follow that AWD causes the lower yields at that site. In fact, experimental data given in chapter 4 of this publication show no significant effect of AWD on yield. The use of hybrid rice is more common in WJX and might account for the higher yields there. However, within TL, farm-level yield was not correlated with the use of hybrid seed, casting some doubt on this explanation.

Because farmers at the two sites do not practice a pure form of either continuous flooding or AWD, a comparison of yields between the two sites is not necessarily meaningful. Thus, as a first step, yield was correlated with the AWD score (see figures 2a and 2b for a scatter plot of these two variables for each year separately). The coefficient was negative and significant at the 10 percent level, suggesting a negative effect of AWD on yield of approximately 1 ton per hectare. (Since a low AWD score indicates irrigation management that is closer to continuous flooding, a negative coefficient indicates that continuous flooding is associated with higher yield).

Figure 2a. Yield versus AWD scores, 1999 WS rice, ZIS, China.

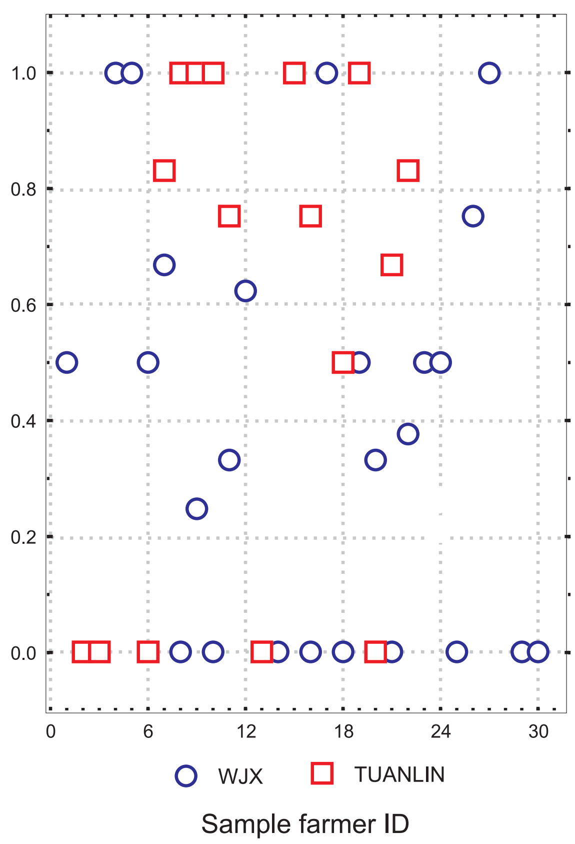
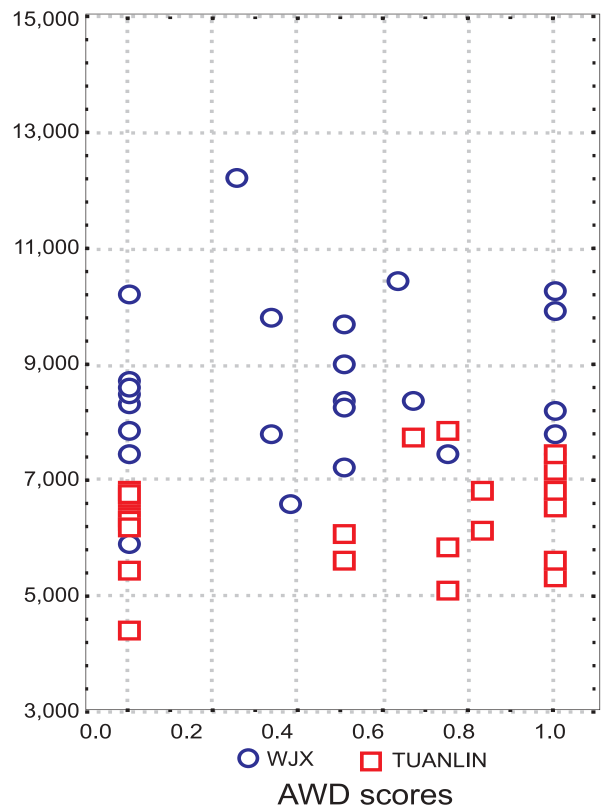


Figure 2b. Yield versus AWD scores, 2000 WS rice, ZIS, China.



But this correlation between the AWD score and yield may simply reflect the higher yields at WJX, where farmers' irrigation management was closer to continuous flooding than in TL. While different techniques of irrigation management could be responsible for the higher yields at WJX, there are other factors that could be responsible as well, such as input use (which was higher at WJX) or unobserved soil quality. In an attempt to control these effects, we estimated a production function with per-hectare yield as the dependent variable. Independent variables included various inputs (e.g., fertilizer, labor), dummy variables for sites and years, the AWD score, and interactions of the AWD score with the year and site dummies (see table 12).

Other than the constant term, only two variables were statistically significant at the 5 percent and 10 percent levels: One was herbicide cost, and the other, insecticide cost (with a negative sign). Using appropriate combinations of the interaction terms, estimates of the effect of AWD on yield were constructed for each combination of site and season (see table 13). The largest effect was noted for WJX in 1999, with increased soil-drying being associated with *increased* yields of about 385 kg per hectare (this estimate was constructed as the coefficient on AWD score plus the coefficient of the AWD score-year interaction).

Table 12. Regression parameters and coefficients of the model used in relating AWD irrigation techniques to rice yield, wet season rice 1999–2000, ZIS, Hubei, China.

Parameters	Coefficient	Standard error
Constant	5,869***	1,185
AWD score	188	1,180
Site dummy	432	773
1= TL		
0= WJX		
Year dummy	1,068	1,005
1=1999, 0=2000		
AWD score * site	-1,101	1,068
AWD score * year	197	1,277
Herbicide (yuan/ha)	15.3**	7.1
Insecticide (yuan/ha)	-5.8*	3.0
Crop care labor (person- days/ha)	15.0	12.6
Nitrogen (kg/ha)	0.5	2.8
Phosphorus (kg/ha)	16.6	14.1
Potassium (kg/ha)	2.8	4.6
Manure (kg/ha)	0.02	0.04
Adjusted R^2	0.22	
R^2	0.32	

*10 percent level of significance.
**5 percent level of significance.
***1 percent level of significance.

Table 13. Estimates of effect of AWD on yield, by site and year.

Sum appropriate regression coefficients		
	1999	2000
TL	-716	-913
WJX	385	188
Standard errors and t-statistics of estimated effects		
	1999	2000
TL	2740	1693
	(t=0.26)	(t=0.5193)
WJX	2348	1180
	(t=0.16)	(t=0.16)

However, the standard error for this effect was more than 2 tons per hectare (see the second matrix in table 13), so that the effect of AWD on yield was statistically insignificant. The estimates of the effects of AWD on yield for other site-season combinations in table 13 were also not significant. Thus, after controlling for effects of sites and years and input use, our conclusion is that AWD has essentially no discernible effects on yield, in agreement with the experiments reported in chapter 4 of this publication.

Profitability of Rice Production

A major determinant of the acceptability of any technology at the farm level is the economic benefit that the farmers stand to derive from the adoption of the technology. This applies to the AWD method of irrigation currently being introduced to the farmers in ZIS. Farmers will be more likely to adopt this technology only if they will clearly get an economic benefit from its adoption. So we assessed the economic feasibility of AWD based on the profitability of rice production of TL and WJX farmers. This section focuses on the comparison of the economic performance of rice production in the two sites through a detailed analysis of costs and returns for the two seasons covered by the study.

Costs of Rice Production

Costs consist of all expenses incurred from land preparation up to the time the unhusked rice is sold or stored for future use. The costs of production are classified into two main categories; the costs for material inputs and labor costs. The costs for material inputs include money spent on fertilizers, insecticides, herbicides, seeds, power (fuel and oil and rental costs for machinery) and on water as represented by irrigation fee payments. Labor costs include hired labor and imputed family labor. The standard procedure of valuing family labor at the mean wage rate of hired labor within the area of study was used in estimating the imputed labor costs. The evaluation procedures assume that the opportunity cost of family labor is equivalent to the wage rate that a family member will receive if he or she works in another farm. These imputed costs are likely to be overestimated if the opportunity cost of family labor is lower than the wage rate.

Among all items of costs, the dominant item was labor, roughly 53 percent for TL and 55 percent for WJX (table 14). Ninety percent of this labor cost is imputed as labor costs. This caused a big discrepancy between the total paid-out costs and total costs. Only a minimal amount was paid out to hired laborers outside of the family.

Table 14. Comparative profitability of wet-season rice production, TL and WJX, ZIS, Hubei, China.

	WS rice, 1999		WS rice, 2000		Average	
	TL	WJX	TL	WJX	TL	WJX
Gross return (yuan/ha)	6,956	7,514	5,312	6,966*	6,008	7,240*
Costs of production (yuan/ha)						
Material inputs						
Fertilizer cost	726	749	753	852	741	800
Insecticide cost	114	124	72	92	90	108
Herbicide cost	36	59*	25	44*	29	52*
Seed cost	229	416*	121	356*	167	386*
Irrigation fee	338	564*	254	621*	290	593*
Power cost	245	237	257	385	252	311
Other costs	288	396	262	261	273	328
Labor costs						
Hired labor cost	233	124	256*	138	246*	131
Imputed labor cost	1,610	2,803*	2,048	3,439*	1,862	3,121*
Total paid-out cost	2,208	2,670*	2,000	2,748	2,088	2,709*
Total cost	3,818	5,472*	4,048	6,187*	3,950	5,829*
Returns over paid-out cost	4,748	4,845	3,312	4,219*	3,920	4,531*
Net return	3,138*	2,042	1,265	780	2,057	1,411

*Mean values are significantly higher than at the other site at the 5 percent level of significance.

The amount spent on fertilizer does not differ much between the two sites. On average, both sites spent about 740 to 800 yuan per hectare or about 14 to 19 percent of total costs. The WJX farmers spent more for seeds and paid higher irrigation fees than the TL farmers. The WJX farmers used pure hybrid seeds that were costlier than the seeds of conventional varieties. Since volumetric pricing of water is practiced at ZIS and pumping costs are directly proportional to the amount of water pumped, WJX farmers who consumed more water paid higher irrigation fees than TL farmers.

Of the material inputs, insecticide and herbicide costs are the least important considering that the costs account only for about 2 percent of the total costs. In summary, the average per hectare costs of producing one wet-season rice crop for WJX amounts to 5,879 yuan per hectare, which is significantly much higher than the 3,950 yuan for TL. A similar relationship holds true for total paid-out costs even though the magnitude of the difference is not statistically large. Half of the difference in paid-out costs between the two sites is due to more money spent on irrigation. However, this is not all due to greater water consumption in WJX. Unfortunately, we do not have data on water applied to the field although the WJX farmers tended to have a greater depth of water at the end of the irrigation event.

Returns to Rice Production

The gross return to rice production was computed by multiplying the yield per hectare by the price of unhusked rice (yuan/kg). The average gross value of production differed substantially between the two sites, with the farmers in WJX and TL receiving per hectare gross returns of 7,240 yuan and 6,008 yuan, respectively (table 14). The difference was due to both higher yields and higher farmgate prices in WJX. The mean price of unhusked rice that the TL farmers received was lower by about 0.09 yuan per kg than what the WJX farmers received; the TL and WJX farmers received an average price of 0.83 yuan per kg and 0.92 yuan per kg, respectively. This price difference could be attributed to differences in the variety that farmers planted and to some specific factors peculiar to a site.

The returns over paid-out costs are estimated by deducting the total paid-out costs from the gross returns (table 14). This represents the returns to family labor, management and land, and the way that farmers usually considered their farm income. But, as explained earlier, we should attach some opportunity costs (value) to family labor. On average, the returns over paid-out costs in TL and WJX were about 3, 900 yuan and 4,531 yuan, respectively. The WJX farmers got significantly higher returns over paid-out costs than the TL farmers. However, the TL farmers obtained a net return overall cost of 2,057 yuan/ha while the WJX farmers obtained only 1,411 yuan/ha. As indicated elsewhere this was due to the heavy use of family labor by the WJX farmers.

Summary and Conclusions

Urbanization and industrialization posed a serious threat to water usually allocated to agriculture. While water commands a higher price in the urban and industrial sectors, it is being wasted by inefficient use for irrigation of agricultural production systems. For quite sometime now, agronomists, economists and water and irrigation scientists have been attempting to manipulate the basic irrigation parameters to cut the total amounts of water applied to irrigated rice production systems through WSI techniques.

In general, the TL farmers were more likely than the WJX farmers to wait until their fields were dry before applying irrigation water, as evidenced by their higher AWD scores. However, there was less difference than was initially expected between the two sites in terms of adoption of water-saving practices. This was especially true in the year 2000, a relatively dry year, when farmers at both sites allowed their fields to go dry before applying irrigation water (unfortunately, we do not have data on whether or not this soil-drying was voluntary or was forced upon them by the operation of the irrigation system). It is important to note that the soil status immediately before irrigation events varied considerably among farms, and that many farmers did not practice a pure form of either AWD or continuous flooding.

The adoption of AWD appears to have little effect on input use. While rice yields were significantly higher for farmers in WJX, our analysis indicated that, controlling for site effects, year effects, and input use, adoption of AWD has no significant effect on yield, either positive or negative.

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Chapter 6

Water Productivity in the Zhanghe Irrigation System: Issues of Scale

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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—

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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.

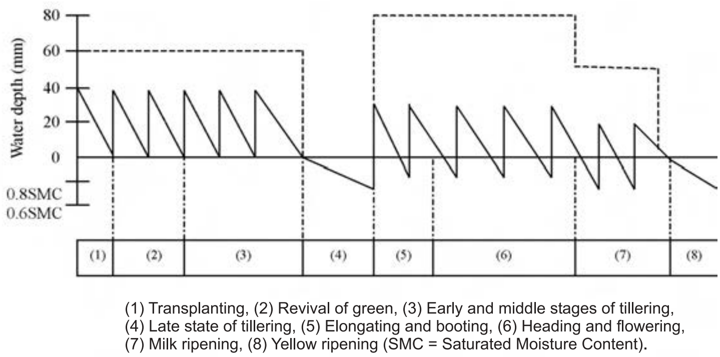
Water Savings

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.



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.

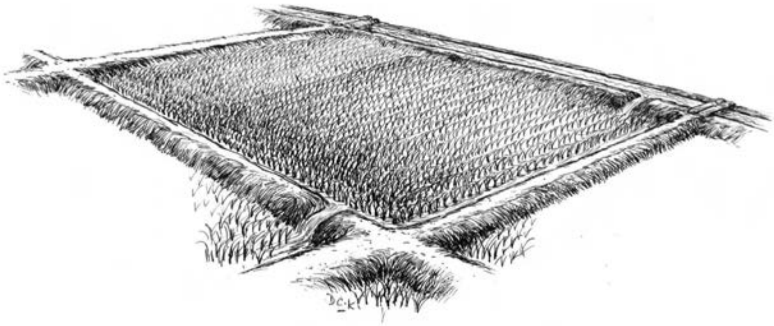
Water-saving practices at the farm scale, with the objective of reducing supplies to farms, do not necessarily lead to transferable savings at the basin scale—where the objective is for rice irrigation to deplete less of the basin water resource. Water savings, as we will demonstrate, constitute a phenomenon 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.

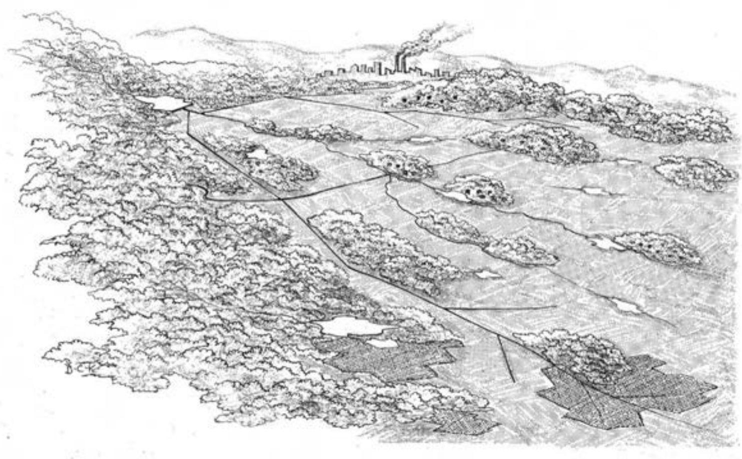
For the research we selected six fields in two sites, one site to represent situations where AWD irrigation is said to be widely practiced and another site where AWD irrigation is said not to be so common. One site was selected near the Tuanlin Irrigation Experimental Station (with AWD irrigation), about 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.

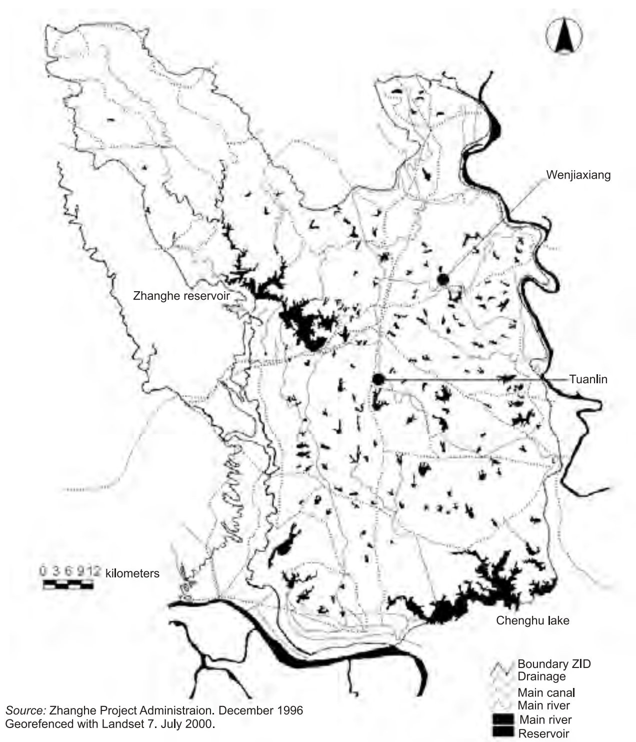


For this research, the two sites representing this scale are the TL and WJX pilot areas. The TL pilot area is irrigated by the first branch of the third main canal and a small-sized reservoir upstream. The total area is 287 hectares of which about 41 percent are rice fields. The WJX pilot area is supplied 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.



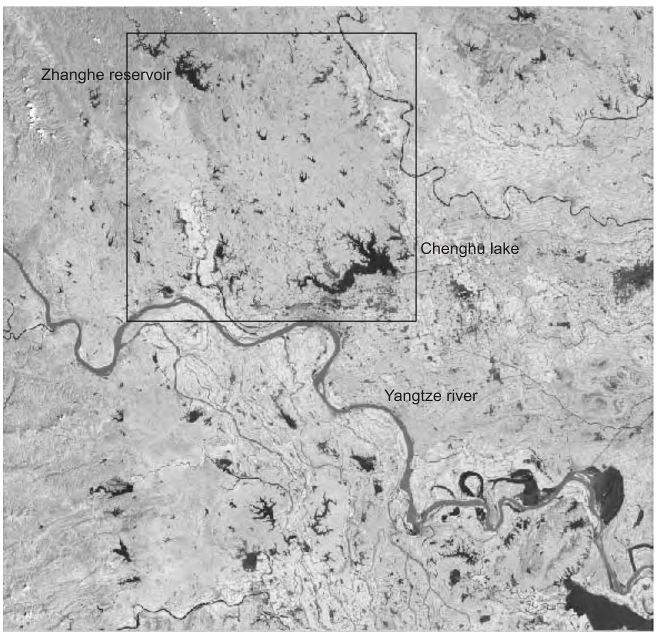
Note: While the landscape is dominated by agriculture other nonagricultural uses of water are also very important. Water bodies are a prominent feature in the landscape.

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

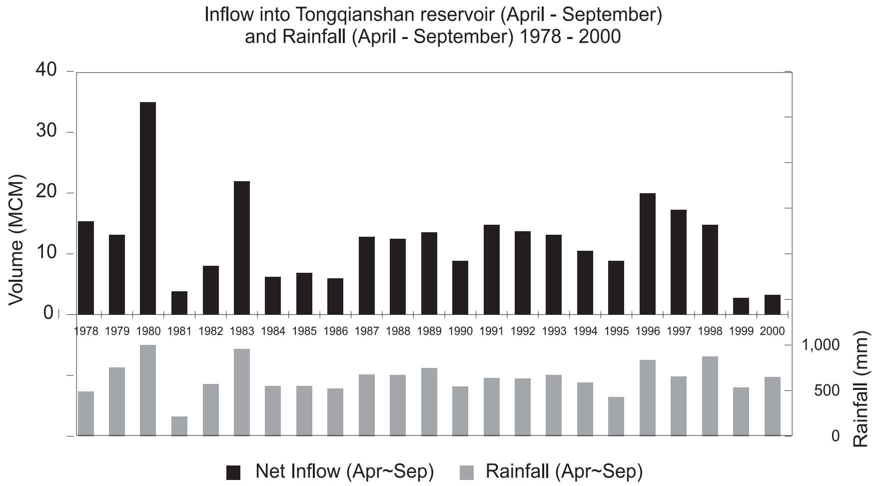
Note: Yield data were obtained from a socioeconomic survey with a sample size of 30 except for TL in 1999 where the sample size was 22 households (2 outliers were eliminated).

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).

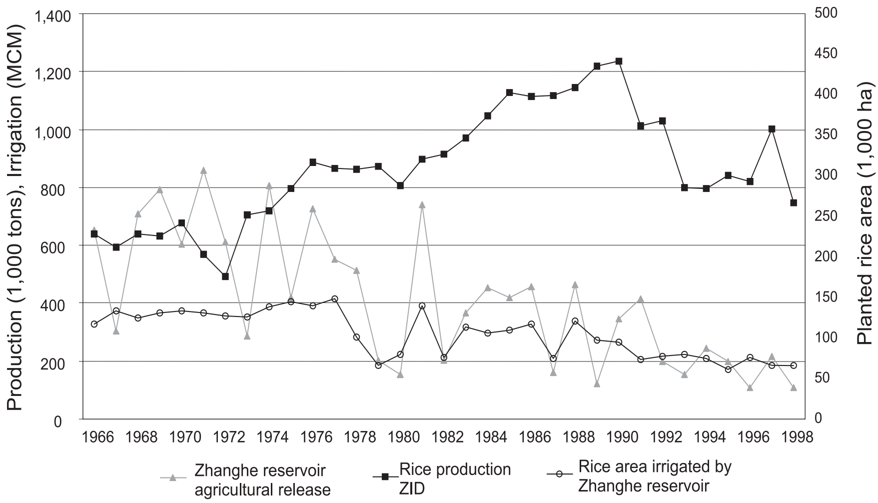
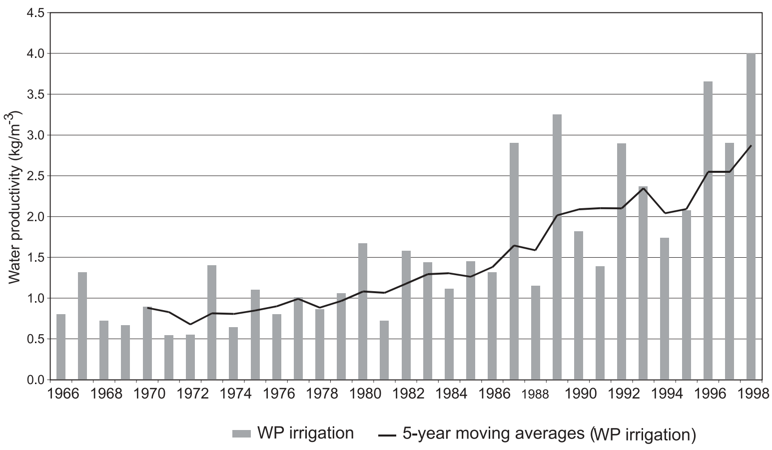


Figure 8. Trend of $WP_{irrigation}$ (1966–1998).



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.

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[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.

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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

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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.

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