Agricultural water management in China

中国农业用水管理

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The Australian Centre for International Agricultural Research (ACIAR) was established in June 1982 by an Act of the Australian Parliament. Its mandate is to help identify agricultural problems in developing countries and to commission collaborative research between Australian and developing country researchers in fields where Australia has a special research competence.

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Foreword

ACIAR has supported collaborative research on water management in agriculture in China for more than 15 years. Our research started small but developed into a substantial body of work during a time when both countries assigned increased priority to water in response to predictions of worsening shortages for agricultural production. The period corresponds with the liberalisation of markets and rapid economic development in China, with increased demands for water from industries and urban users. The period followed a switch away from major new developments of water resources to improving the efficiency of using a more or less fixed resource, particularly in the arid regions of north-western China. In Australia it corresponds with the establishment of property rights and water trading, and increased allocations of water for environmental purposes — a culmination of decades of research and policy development.

Increased efficiency of water use depends on the scale that we are examining, and ranges from national scale right down to individual farmer's fields. ACIAR research has addressed all the scales, and more recently tried to understand the interactions between them, to integrate them and to integrate scientific and economic approaches. This body of research has been brought together in these Proceedings. The papers were presented at an ACIAR-sponsored session of the International Commission on Irrigation and Drainage's 19th International Congress on 14 September 2005. The papers summarise the joint efforts of scores of researchers from China, Australia and international agricultural research centres involved in several ACIAR projects. We are pleased to publish these Proceedings to record this body of research, to guide choices for future investments in research, and to inform decision makers.

Peter Core
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Summary

The papers in these proceedings bring together the results of research projects on agricultural water use arising from ACIAR-supported research over the past decade. Our research has focused on the water-scarce Yellow River Basin of northern China, with detailed research in the wheat- and maize-growing areas of the North China Plain (Hebei and Henan) and the Yinchuan Plain (Ningxia), and the intensive rice-growing area in central eastern areas (Hubei). The research ranges in scale from studies made in farmers' fields, usually with their participation, through to consideration of water allocation in the entire Yellow River Basin. Several of the papers are introduced with striking information on water scarcity in China, the dependence on irrigation to feed the huge population, and the reputation of agriculture as an inefficient user of water during a time when demand for other uses is increasing. The purpose of this summary is to present an overview of the entire proceedings in just a few pages—a fuller picture and greater details are available in the individual papers.

In the North China Plain the depth to the groundwater is dropping by as much as 1 m each year and it is predicted to be too deep for abstraction for irrigation within 20 years. Detailed work at the Chinese Academy of Sciences' research station at Luancheng (Hebei Province) has linked the increasing depth of the watertable to irrigation of wheat on the plain, as well as to reduced recharge from the regional groundwater. Their research, summarised by Hu and McVicar, showed that it is possible to reduce irrigation water applications to wheat in this part of the plain by 50% in most years, or a reduction from 3–5 irrigations per season to only 1 or 2. Incentives for reducing applications of the groundwater for irrigation include reduced pumping and labour costs, even though there is no direct charge for the groundwater. Modelling suggested that there is scope for reducing water applications even further by reducing evaporation from soil by the use of mulches. It was concluded that water saving measures would be effective in reducing the decline in watertable levels.

Chen and his colleagues developed a model for nitrogen and water management, based on detailed soil, crop and meteorological measurements at Luancheng and at two other field sites on the North China Plain. They also showed excessive water use and linked it to losses of nitrogen, which is also applied in excessive quantities to maize and wheat crops grown in rotation. Irrigation water and nitrogen applications can be reduced while maintaining crop yields even in years with lower than average rainfall. The excessive applications result in the transport of nitrate from the root zone to the groundwater, often to the extent that the groundwater has nitrate concentrations that make it unfit for human consumption. The research also showed that nitrogen is lost in the form of ammonia gas, as it is applied as urea to alkaline soils. Simple changes in practices such as irrigating immediately after urea application or incorporating it at depth markedly reduced the amount of urea lost to the atmosphere. They showed that it was possible to reduce urea applications to maize crops by 100 kg N/year as well as reduce irrigation by 200 mm while maintaining crop yield and increasing profits. It was also clear that recommendation for changes to urea applications were readily adopted by farmers, but that those related to reducing irrigation were not adopted.

Wei et al. examined the reasons for lack of adoption of water-saving practices in Henan Province. From surveys, they found that the farmers have little awareness of the environmental aspects of water and nitrogen use or the concept of efficiency of their use. Their main interest is in ensuring grain self-sufficiency and they simply have no perception that there is a need to improve their water use or adopt water-saving techniques. The farmers' incomes are low and they have little capacity for either paying more for their water use or investing labour or time in improved water use. Wei et al. also found that extension services are not having a great influence on farmers' irrigation behaviour, and recommended that educational activities are needed in addition to financial incentives. Khan summarises some lessons and ideas for reducing financial barriers for farmers to

invest in water-saving measures in irrigation systems and on individual farms in Australia. In particular, he introduces the idea of water leasing as means of meeting the need for investments in water-saving techniques in the face of low prices for the products of irrigated agriculture.

In the Liuyuankou Irrigation System, near the Yellow River in Henan Province, Feng et al. found that water-saving practices could be applied to rice production. The use of alternate wetting and drying irrigation instead of continuous flood irrigation reduced water applications and maintained rice yields, resulting in greater water productivity (grain produced per volume of irrigation water) by 30–60%. The technique is particularly suited to areas with shallow (non-saline) groundwater. They also tested the more radical alternative of growing rice without standing water—'aerobic rice'— and demonstrated even greater water productivity, but with reduced yields. There is probably scope for improving yields of aerobic rice by developing varieties specifically for this purpose. The work of Hafeez and Khan at Liuyuankou, at larger scale using remote-sensing technologies, and analyses of water use at irrigation system scale by Molden et al., emphasised the need to reduce non-beneficial evaporation of water from the irrigation area and particularly from fallow land. Lou et al. show there is scope to improve water use at the irrigation-system scale by better conjunctive use of surface- and groundwater.

Further inland in the Yellow River Basin, Ali and Wu showed that irrigation water was applied in volumes much greater than needed for crop production in the Yinchuan Plain, Ningxia Autonomous Region. At the northern end of the plain there is a shallow watertable (1–2 m), extensive salinisation of the surface soil, and discharge of salt to the Yellow River. In general, the groundwater is too saline for use as irrigation water unless it is diluted with fresher water abstracted from the Yellow River. Simple changes in irrigation techniques, from flood to furrow methods, were effective in reducing excess water applications, and can be helpful in reducing water additions to the groundwater, and reducing salinisation. Reducing leakage of water from irrigation channels was also shown to be important in reducing the extent of shallow watertables.

The work of Heaney et al. investigated water use and allocation at the scale of the whole Yellow River Basin. It is based on the premise that improvement in the use of the massive water resource infrastructure in the basin can improve water-use efficiency and con-

tribute to reducing poverty. They demonstrate the potential for overall increased productivity of water, both in terms of economics and grain production, of re-allocating water resources from low-returning to high-returning regions within the basin. The current administrative water-allocation procedures could be adapted to bring about re-allocations, but are constrained by demanding information requirements. They make the case for the development of formal water markets to bring about changes in allocations so that water use is transferred to higher-value uses at the large scale. This implies the need for private, secure and transferable property rights for water, which, in turn, requires fundamental reforms in terms of legislation, institutions and regulatory frameworks.

Further south, in the subtropical monsoonal areas where rice is the principal cereal, ACIAR-supported research has focused on the Zhanghe Irrigation System near Wuhan (Hubei Province), in the Yangtze River Basin. Replacing traditional continuous flooding with alternate wetting and drying irrigation allows water savings while maintaining rice yields in areas with shallow watertables. Despite being well endowed with water in comparison with the Liuyuankou in the Yellow River Basin, water-saving measures have been more widely adopted in Zhanghe than in Liuyuankou. This is due to reductions in the water allocation to irrigation and increased allocation to other uses. This clearly demonstrates that farmers can adapt to reduced water supplies in Zhanghe, which has some flexibility because of numerous pond within the irrigation area and the summer monsoonal rainfall. In drier areas, groundwater may be able to function as a buffer in water supplies, taking on the role played by small ponds at Zhanghe.

George et al. describe how they adapted and tested computer-based systems to the operation and management of a major canal within the Zhanghe system, and present financial analyses during a period when pricing arrangements for irrigation water were changing quickly. It was clear that there was no direct link between costs of operation and management of the canal and the price of water— neither area-based nor volumetric pricing came near to meeting the costs of supplying irrigation water. In addition, asset management for irrigation infrastructure demonstrated the longer-term investments required to replace and maintain installations. Financial analysis showed that current prices for irrigation water were much too low meet the costs of delivery or infrastructure maintenance.

Jayawardane and his colleagues describe the controlled land application of effluent water to recover water for irrigating crops and with excess drainage water of sufficient quality to meet environmental standards. The technology, developed in Australia, was adapted for use in China, for waste waters that are not grossly contaminated by industrial pollutants. Adaptations are required for its use in northern China to take account of the small landholdings, differing soil and groundwater conditions, and the cold winters.

In aggregate, the papers reinforce the need for improvement in agricultural water use in China. Scientific and engineering research has demonstrated that reduced water use by agriculture is possible while simultaneously maintaining crop yields and maintaining farmers' incomes, with potential for environmental improvement, and economic efficiencies at national level. It is also clear that adoption and implementation of research findings at the scales of individual farmers' fields, irrigation systems, or in the entire Yellow River Basin, are still limited. Financial and institutional constraints to adoption are readily identifiable but are not readily overcome without fundamental reforms in terms of legislation, institutions and regulatory frameworks. In Australia, such reforms took decades to introduce, and it can be expected that a similar time frame is required in other countries and perhaps longer in countries with large populations living in rural poverty. Future research needs to steadily build the case for reforms while equipping farmers and irrigation system operators and other water-resource managers with the means to respond to the reforms.

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概 要

  这本论文集中的论文是过去 10 多年当中山澳大利亚国际农业研究中心（ACIAR）资助的有关农业用水方面研究项目成果的汇总。我们的研究重点在华北极度缺水的黄河流域，对华北平原（河南、河北）和银川平原（宁夏）的小麦和玉米种植区以及华中东部（湖北）的水稻种植区进行了详细的研究。 研究范围从通常由农民参与研究的农田到考虑整个黄河流域水资源配置的流域。有几篇文章介绍了引人关注的中国缺水情况，依赖灌溉养活庞大的人口情况，以及在其他用水需求增加的情况下农业被认为是用水利用效率低下的用户的名声。这个概要的目的是用几页纸的文字展示论文集的总体情况－即提供一个全景，更详细的情况在每篇文章中介绍。

  在华北平原地下水位正在以每年 1 米的速度下降，据预测在未来的 20 年内地下水埋深将加深而无法用于灌溉。在中科院栾城（河北省）实验站的研究工作已把华北平原地下水埋深增加和灌溉小麦以及区域地下水补给减少的情况相互联系起来。他们的研究（山胡和 McVicar 总结）表明，在实验站所处的平原区在大多数年份小麦的灌溉用水量可以减少 50%，或将灌溉次数由每季 3 至 5 次减至 1 至 2 次。虽然对地下水不直接收取水资源费，但农民还是愿意减少用水，减少提取地下水灌溉的动力是降低提水和劳动成本。模型成果显示，应用地膜可以减少土壤蒸发量，从而可以进一步减少灌溉用水量。研究的结论是节水措施对减轻地下水位下降是有效的。

  基于在栾城和华北平原上另外 2 个实验站的土壤、作物和气象等详细资料，陈和他的同时们开发了一个用于氮和水管理的模型。他们的研究也表明灌溉存在过量用水的问题，在小麦和玉米轮作区也存在过量施用氮肥的问题，他们在模型中把过量用水和氮肥流失联系起来。即使在降雨量少于平均降雨量的年份，在维持相同的作物产量情况下也可以减少灌溉水量和氮肥施用量。水肥的过量施用导致氮素从根系层向地下含水层运移，常常使地下水中氮的含量过高而不适合被人类饮用。研究还表明，当把尿素施用到盐碱地的时候，氮是以氨气的形式损失掉的。在施用方法上作些简单的改善，如在施用尿素后立即灌溉或将尿素施用到土壤中可以显著地减少尿素向空气中的流失。他们的研究表明，对于玉米尿素的施用量减少 100 公斤/年、灌溉水量减少 200 mm 的情况下，也可以维持相同的产量且农户的效益增加了。改变尿素施用的建议易被农民接受，而减少灌溉用水的建议没有被接受。

  魏等研究人员分析了节水灌溉措施在河南省没有推广开来的原因。他们在调查中发现，农民对水和氮肥的应用对环境的影响或它们的利用效率了解甚少。农民的主要兴趣在于粮食自给，他们对改善用水或采取节水技术没有概念。农民的收入低，他们没有能力为用水支付更多的费用，也不愿为改善用水投入更多的劳力和时间。魏等人发现，推广服务对改变农民的灌溉习惯没有太大的影响，建议除了经济激励手段之外还应当采用教育等措施。可汗（Khan）总结了澳大利亚灌区和农场在减少财政障碍使农民投资发展节水灌溉方面的经验和理念。他特别介绍了在灌溉农产品价格低的现实情况下，有偿转让用水作为解决发展节水灌溉技术所需投资的理念。

在河南省黄河附近的柳园口灌区，冯等人发现节水灌溉措施可用于水稻生产。用干湿交替的灌溉方法代替持续的淹没灌溉方法可减少用水并维持水稻产量，可将水分生产率（单位灌溉水量生产的粮食产量）提高高 30－60％，这种方法特别适用于地下水位埋深浅的地区（无盐碱化问题）。他们还进一步试验了在田间无淹没水层的水稻种植方法，可以进一步提高水分生产率，但是产量降低了。通过培育专门的品种有可能提高旱稻的产量。罕费兹（Hafeez）和可汗（Khan）在柳园口灌区大范围内应用遥感技术，曼顿（Molden）等人分析了灌区层次上的用水情况，强调要减少灌区的无效蒸发，特别是减少休耕地上的蒸发。娄等人的研究表明，通过地表水和地下水联合应用可以改善灌区的用水效率。

在黄河流域的内陆地区，阿里（Ali）和吴的研究表明，在宁夏回族自治区的银川平原灌溉用水量比作物需水量要高的多。在该平原的北端地下水埋深很浅（1 至 2 米），存在严重的盐碱化问题，盐分被排到黄河。总的来说，地下水含盐量太高不能用于灌溉，但用从黄河引取的水稀释后可以灌溉。只要用沟灌代替漫灌就可以有效地减少过多的用水量，也就可以减少对地下水的补给量，从而减轻盐碱化问题。研究还表明，减少灌溉渠道的渗漏量对减轻地下水埋深太浅有重要作用。

黑尼（Heaney）等人研究了整个黄河流域的用水和配水情况。这项研究基于改善黄河流域的水资源基础设施可以改善用水效率和有利于减少贫困的理论。他们展示了整体上提高水分生产率的潜力，包括经济上和粮食生产上的潜力，或在流域内将水从低回报的行业转移到高回报的行业。现行的配水管理程序可适应于水资源的从新分配，但受到了需水信息的影响。他们研究了正式的水市场发展，在水资源配置上带了变化，在大的范围内使水向高价值的用途转移。这意味着需要有私有的、有保障的和可转移的水权，反过来，这需要在立法、体制和规章制度框架上进行彻底的改革。

在南方的亚热带季风区，水稻是主要的粮食作物，ACIAR 资助的研究集中在位于长江流域湖北省武汉附近的漳河灌区。在地下水埋深浅的地区，用干湿交替的灌溉方法代替传统的持续淹灌方法不但节约了水，同时还维持了水稻的产量。与黄河流域的柳园口灌区相比，虽然漳河灌区有充足的水量，但节水措施在漳河灌区应用的比柳园口灌区更为广泛。这是由于在漳河灌区供给灌溉的水量在减少而供给其他用水部门的水量在增加。这显而易见的表明，在漳河灌区农民可以接受供水减少的情况，由于在漳河灌区有许多水塘和夏季季风期的降雨，这使得漳河灌区的水资源具有一定的弹性。像漳河灌区的小水塘所起的作用一样，在较干旱的区域地下水可以对供水起到缓冲的作用。

George 等人介绍了在漳河灌区他们如何调试和试验用于骨干渠道运行和管理的计算机管理系统，并对灌溉用水价格安排变化快阶段的财务分析进行了论述。很明显，在渠道的运行管理费用和水价之间没有直接的关系－按面积收费和按水量收费的情况都不能满足供水成本。此外，灌区基础设施的管理表明，需要长期投资来更新和维护这些设施。财务分析表明，现行灌溉水价太低，无法满足供水和设施维护费用。

Jayawardane 和他的同事介绍了生活污水控制式的土地处理系统应用，既为灌溉作物提供了水源，也使灌溉后排出的剩余水的水质达到环保标准。在澳大利亚开发的这项技术在中国应用于处理没有被工业污染物污染的污水。这项技术在中国北方的应用需要考虑土地占有量小、土壤及地下水条件条件和寒冷的冬季等条件。

总之，这些论文进一步强调了中国在改善农业用水方面的需求。科学和工程研究表明，在减少农业用水的同时维持作物产量和农民的收入是有可能的，这可以在国家尺度上改善环境和经济运行效率。也很明显，研究成果在农田、灌区和整个黄河流域的应用和实施仍然是有限的。研究成果的应用在财政和体制上的约束已十分清晰，但是如果不对法规、体制和机构框架进行根本性的改革，这些问题是难以被解决的。在澳大利亚，这样的改革用了数十年才得以完成，其他国家也需要相同的时间，在那些有大量农村贫困人口的国家也许需要更长的时间。未来的研究需要稳步积累改革案例，同时要使农民、灌溉系统运行人员和其他水资源管理人员有能力对改革作出响应。

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Groundwater use and potential implications for water conservation in the North China Plain

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Abstract

Agricultural productivity in the North China Plain (NCP) is heavily dependent on groundwater exploitation. Taking the piedmont plain of the Taihang Mountain in the northern part of the NCP as an example, the groundwater table is declining at a rate up to 1 m per year. Groundwater resources could be depleted in 20–30 years at such a rate. Therefore, it is of paramount importance to adopt water-saving practices in the NCP to maintain current agricultural sustainability to feed the increasing population. The Chinese Government has been aware of this problem and has supported many research projects to analyse factors contributing to groundwater depletion and to find effective water-saving measures. This paper reports our efforts to develop and implement water-saving agriculture in the piedmont of Taihang Mountain where long-term field experiments, monitoring and extension have been conducted, including matching crop rotation systems to climate pattern, better irrigation scheduling and methods, no-till technology to reduce soil evaporation, and highly water-use efficient cultivars. These techniques have shown great potential for water-saving in the NCP as demonstrated at the Luancheng Experimental Station in the piedmont of Taihang Mountain.

华北平原的地下水利用及对水保的潜在影响

摘要：在华北平原农业生产在很大程度上依赖于对地下水的开发。以华北平原北部的太行山平原为例，地下水位以每年1米速度下降。如果以这样的速度发展下去地下水资源将在20至30年内耗竭。因此，在华北平原最为重要的是采用节水措施以维持现行的农业生产，养活日益增加的人口。中国政府已经认识到了这个问题，并资助了许多研究项目来分析影响地下水消耗的因素，探讨有效的节水措施。这篇论文介绍我们在太行山区开发和应用节水农业方面的工作，我们在这里开展了长期的田间实验、监测和推广工作，包括按照气象条件确定轮作模式、应用较好的灌溉制度和方法、减少土壤蒸发的免耕技术以及水分高效利用栽培方法等。在太行山平原区的栾城实验站（LES）的试验证明，这些技术在华北平原具有很大的节水潜力。

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Introduction

Agricultural sustainability in China, especially in the North China Plain (NCP), is mainly determined by available water resources. As stated by Brown and Halweil (1998), water shortage in China could shake world food security. The NCP is one of the major agricultural areas in China; it covers an area of 3×10^5 km^2 and has a population of over 300 million people. It produces about one-fifth of the nation's food. However, average water per person is about 500 m^3 per year in this region, which is only one twentieth of the world's average. The average annual precipitation in the region ranges from 500 mm to 650 mm and is highly variable between years; within a year more than 70% of the annual precipitation is distributed from July to September. In general, such a low precipitation is not enough to meet normal crop growth demand (ET). In 1989, more than 80% of the water resources (surface and groundwater) in this region were used for agricultural irrigation (Liu and Wei 1989). With less availability of surface water from rivers and lakes, farmers are forced to pump more groundwater to meet irrigation demand, which has caused watertable decline in both shallow and deep aquifers as in the Southern High Plains (Ogallala aquifer) (Kromm and White 1992; Opie 1993). In the northern part of the NCP the depth of the watertable has increased at 0.64 m per year from 1964 to 1984 and about 1.22 m per year from 1984 to 1993 (Wang et al. 2002). A 50,000 km^2 groundwater funnel has formed in this region; this is the largest groundwater funnel in the world. It is estimated that the shallow aquifer will be used up within 20–30 years at current rates of utilisation (Hu and Yin 1999). To cope with the water shortage in this region, four procedures of water-saving agriculture have been practised: (1) rational utilisation of agricultural water resources; (2) water-saving irrigation; (3) agronomic water-saving techniques; and (4) agricultural management (Wang et al. 2002).

The objectives of this study were to analyse the factors contributing to groundwater table decline in the piedmont plain of Taihang Mountain on the North China Plain, and to propose effective and feasible measures of water-saving to reduce irrigation and retard the rate of groundwater table decline for farmers, based on our long-term field study and extension at the Luancheng Experimental Station (LES).

Factors contributing to the decline in the groundwater table

The piedmont plain of Mt Taihang is a typical high-yield agricultural area, located in the northern part of the NCP. This region relies mainly on groundwater for irrigation and rainfall is highly variable. The groundwater table has been declining since the 1970s at a rate of up to about 1 m per year (Figures 1 and 2). The main factors contributing to the continuous decline in the groundwater table are as follows, based our long-term observation and study.
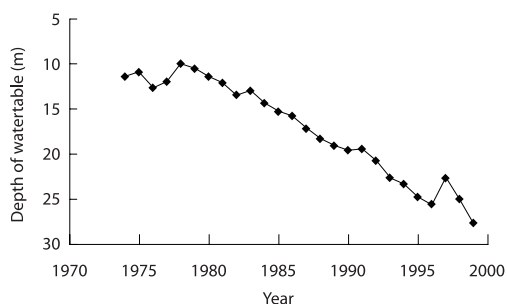
Figure 1. Increase in depth of the watertable in Luancheng County on the North China Plain, 1970–2000
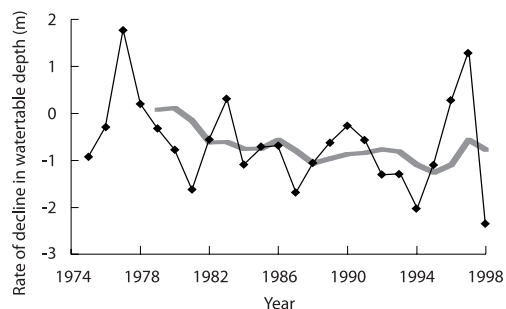
Figure 2. Rate of decline in the depth of the watertable in Luancheng County on the North China Plain, 1974–1998. Red line is moving average

Decrease in precipitation due to drought and warmer climate

Average annual air temperature has increased by 0.1°C every decade since the 1950s (Table 1), while average annual precipitation has fallen by 135 mm per year from the 1950s to 1990 (Figure 3). Average annual rainfall was 555 mm in the 1950s, 514 mm in

the 1960s, 4946 mm in the 1970s, 436 mm in the 1980s, and 421 mm in the 1990s. The reduced precipitation has significant impacts on the rate of decline of the groundwater table (see Figure 4). The relationship between precipitation and decline rate of groundwater table can be expressed as follows:

$$Y = 2.4144 - 0.0037X \quad (R^2 = 0.4783) \quad (1)$$

Y is the rate of decline in the groundwater table (m) and X is annual precipitation (mm). Annual precipitation of 652 mm gives a zero rate groundwater table decline. Every 100 mm per year reduction of rainfall will lead to groundwater table decline by 0.37 m. This means that 0.5 m/year of the rate of decline is caused by the reduction in rainfall over the past 50 years. This accounts for about 50% of total decline rate in the groundwater table. The rainfall decrease is one key factor, though not the only factor contributing to groundwater table decline.

Decrease in recharge from Taihang Mountain due to climate changes and human activities in the upper river

Based on the study of Shi (1995), surface run-off from the mountain area entering the plain fell from 275.3 mm to 44.1 mm from 1950 to 1989 (see R_I in Table 1). One reason is that annual precipitation in the mountain areas also fell. Another reason is that most run-off previously entering the NCP is now captured in mountain reservoirs for both agricultural and urban uses. Assuming that the precipitation fell about 130 mm also in the mountain area, another reduction of about 100 mm run-off was due to human activities (i.e. dams and reservoirs)

The fact that recharges from the mountain area to the plain fell is supported by the groundwater table changes in the plain observed in long-term monitoring data in Gaocheng County in NCP. There is

little rainfall during November to February in this region. The groundwater table was usually rising in these months due to recharge from the adjacent mountainous area. From Figure 5, it can be seen that, since the late 1970s, there has been a falling trend in the rate of rise of the watertable, from 1 m in 1970s to 0.2~0.4 m in 1990s, which implies that lateral flow has decreased.
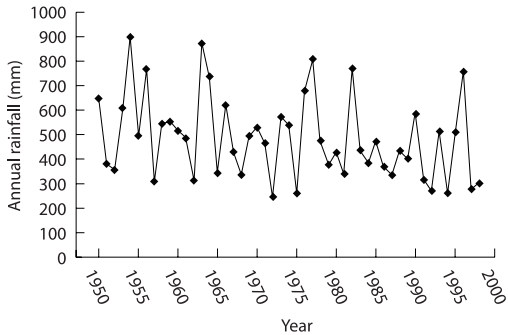
Figure 3. Average annual precipitation in Luancheng County on the North China Plain, 1950–2000
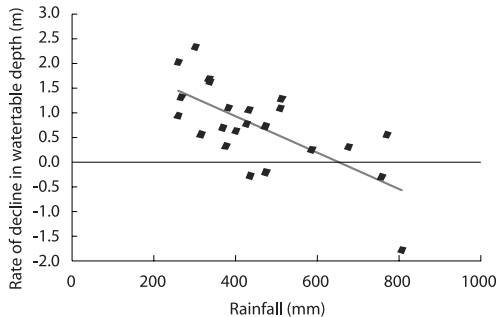
Figure 4. Relationship between precipitation and depth of the watertable in Luancheng County on the North China Plain

Table 1. Estimation of the water resources balance on the Hebei Plain, 1950–1989

Years	Annual average precipitation (mm)	Surface run-off from mountain area (R_I) (mm)	Annual average T (°C)
1950–1959	600.5	275.3	10.1
1960–1969	577.5	160.7	10.2
1970–1979	560.2	108.7	10.3
1980–1989	496.7	44.1	10.4

Source: Shi (1995).

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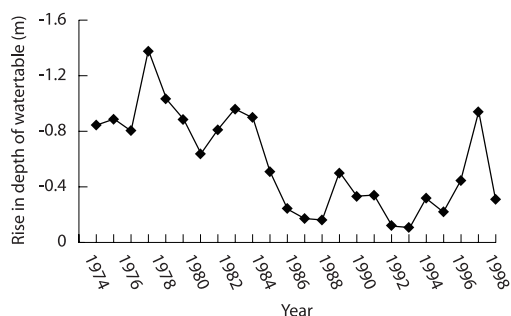
Figure 5. Rate of rise in the watertable in Gaocheng County on the North China Plain, 1974–1996

Intensive cropping systems of winter wheat–maize rotation

The cropping system has changed from three crops in two years to two crops in one year with increasing population and improvements in irrigation, fertiliser treatment, and new crop varieties since the 1970s. The winter wheat–maize rotation is now the dominant cropping system, accounting for 80% of total planted area in this region. But the low and variable rainfall cannot meet the crop's water demand. The average rainfall during the wheat-growing season, from October to June ranges from 60 mm to 150 mm (McVicar et al. 2002); irrigation is therefore necessary for obtaining high yield, especially for winter wheat. ET during the winter wheat growth period is 488.2 mm and rainfall is only 126.8 mm with a deficit of 361 mm (Table 2) Farmers in this region generally irrigate winter wheat 3–5 times each season and maize one or two times per year (Table 3).

Besides irrigation demand for winter wheat due to intensive cropping, the planting area for winter wheat has also increased (Figure 6), which is another important factor contributing to groundwater table depletion. Figure 7 shows the changes in monthly average groundwater table from 1974 to 1998 in Luancheng County in NCP. The decline in the groundwater table

Table 2. Water requirements by winter wheat calculated using the Penman equation recommended by FAO in the piedmont of Mt Taihang, North China Plain[a]

	Month								First 10 days of June	Total growth period (mm)
	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May		
Eto (mm/day)	2.2	0.9	1.3	0.8	1.2	2.2	3.6	4.6	5.1	566.9
Kc	0.85	0.54	0.92	0.33	0.24	0.42	1.14	1.22	0.73	---
Etc (mm/day)	1.87	0.49	1.2	0.26	0.29	0.9	4.1	5.5	3.7	----
Etc (mm/month)	58.0	15.1	35.9	8.2	8.1	28.6	123.1	173.8	37.2	488.2
Rainfall (mm/month)	22.5	6.4	8.8	2.6	6.8	11.2	18.3	34.2	16.0	126.8
Rainfall – Etc (mm)	−35.5	−8.7	−27.1	−5.6	−1.3	−17.4	−104.8	−139.6	−21.2	−361.4

[a] Eto is reference evapotranspiration calculated by Penman equation using data from 1971 to 1998, Kc is crop coefficient, Etc = Eto*Kc. Monthly rainfall is the average from 1971 to 1998.

Table 3. Water requirements of summer maize calculated by Penman equation recommended by FAO in the piedmont of Mt Taihang, North China Plain[a]

	Month				Total growth period (mm)
	11–30 June	July	Autumn	1–20 September	
Eto (mm/day)	5.5	4.4	3.8	3.2	460.2
Kc	0.5	0.81	1.1	1.07	---
Etc (mm/day)	2.75	3.56	4.18	3.42	---
Etc (mm/month)	55.0	110.4	129.6	68.4	363.4
Rainfall (mm/month)	40.6	136.5	119.6	34.9	331.6
Etc – rainfall (mm)	−14.4	+26.1	−10.0	−33.5	−31.8

[a] Eto is reference evapotranspiration calculated by Penman equation using data from 1971 to 1998, Kc is crop coefficient, Etc = Eto*Kc. Monthly rainfall is the average from 1971 to 1998

occurs mainly from April to July, during the growth period of winter wheat, indicating that winter wheat uses a great deal of groundwater. Figure 8 shows that the monthly decline rate of groundwater table has become greater since 1975, and that the monthly decline rate in April is larger than that in May, June and July. Figure 9 shows that there is a negative relationship between of winter wheat planting area and decline rate of groundwater table in Luancheng County in NCP, further indicating that winter wheat uses a great deal of groundwater.

Low water-use efficiency

There is a lack of widespread application of advanced irrigation facilities and techniques to ensure high water-use efficiency (WUE) in cropping.

According to traditional management, seven irrigations are needed in the growing season of winter wheat and summer maize. About 70–80 mm of water are used for each irrigation. The water production efficiency for this system is about 1–1.5 kg/m^3, so there is potential to increase WUE to reduce irrigation water use, as discussed in the following section.

Proposed key effective and feasible measures for water-saving agriculture

To develop best water-saving agricultural management practices, a series of long-term field experiments and monitoring were conducted at Luancheng Experimental Station in the piedmont of Taihang

Figure 6. Change in winter wheat planting area in Luancheng County on the North China Plain, 1945–1995
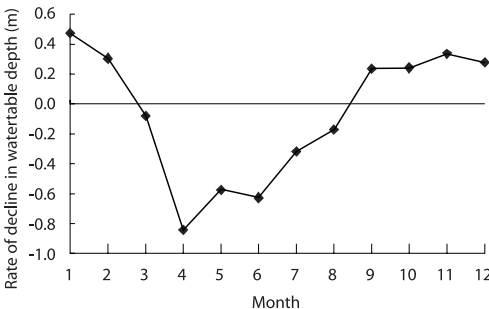

Figure 7. Average monthly change in the depth of the watertable in Luancheng County on the North China Plain, 1974–1998
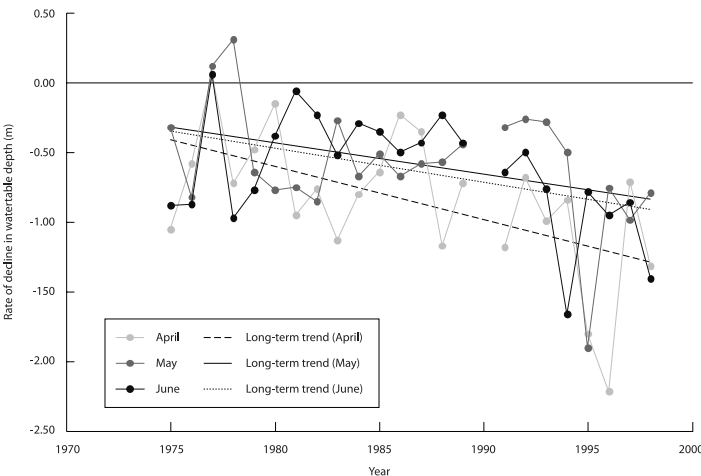

Figure 8. Rate of monthly decline (April–June) in the depth of the watertable in Luancheng County on the North China Plain, 1975–1998

Mountain, including analysing climate change, groundwater resources, crop water use potential, and better irrigation methods and scheduling. Some of the measures developed have been proved to be effective and accepted by farmers. To assess the impact of improvements at the local level, McVicar et al. (2002) developed a method to monitor agricultural WUE for regions, using readily available data.

Adopting cropping systems for better use of precipitation and groundwater resources

The current cropping system of wheat–maize and irrigation management in this region is unsustainable. High yields are mainly maintained by excessive exploitation of groundwater resources. Winter wheat requires large amounts of irrigation and current expansion of wheat acreage cannot be sustained through precipitation. For sustainability of cropping systems, it is recommended to reduce the planting area of winter wheat, and increase the acreage of drought-tolerate crops to match the climate pattern and regional resources. Based on the perceived linkage between winter wheat planting area and the depth of the groundwater table (Figure 9), it is estimated that groundwater table decline will be zero if the area planted to winter wheat is reduced from 25,000 ha to 15,000 ha in Luancheng County. It is feasible to establish a farming system based on pasture and grain crops rotation in this region with animal husbandry development, which will reduce early spring irrigation and avoid the excessive use of groundwater.

Establishing optimised irrigation scheduling

Rational irrigation scheduling is needed to maximise yield and WUE and to minimise ET (especially E) for a given irrigation amount through appropriate irrigation timing and methods. It is essential to understand the relationship between water and yield, including yield and ET, yield and irrigation time, yield and irrigation amount as well as irrigation methods. Much research has been done in this field and several new irrigation theories for water saving have been developed, such as limited irrigation (Xu 1991), regulated deficit irrigation (Nakamura 1989; Guo et al. 1999) and controlled alternative irrigation (Davies and Zhang 1991).

ET-yield relations and irrigation amount for crop water requirement

The relationships between yield and seasonal evapotranspiration (ET) for wheat can be either linear (Hanks and Rasmussen 1982; Musick et al. 1994; Zhang and Oweis 1999) or curvilinear (Aggarwal et al. 1986). Figure 10 shows relationships between yield, WUE and ET at Luancheng Experimental Station for three seasons. The results show that the highest ET did not produce the highest yield, and that WUE is decreasing with increasing in ET in this region. At low levels of ET, crop yield increases quickly with the application of irrigation, but once ET reaches a certain point, crop yield increases slowly and then falls with increasing ET. The yield and irrigation amount has a similar nonlinear relationship. So, with some short-term prediction of rainfall in the growing season it may be possible to optimise the irrigation schedule to reduce irrigation water use as well as ET, to achieve high yield and high WUE.
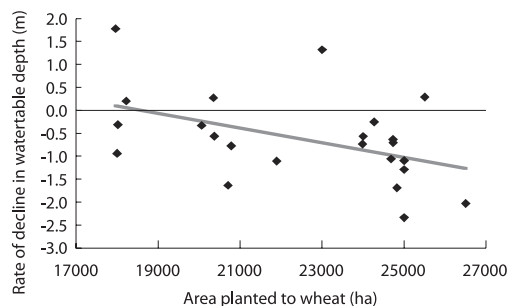
Figure 9. Relationship between planting area (ha) of wheat and rate of decline in the depth of the watertable in Luancheng County on the North China Plain

Crop response to water stress and irrigation time

Crop sensitivity to water stress differs during different growth stages with the most sensitive stage at what is called the crop water critical stage. In the US Southern High Plain, Schneider and Howell (2002) reported that the most critical period to provide adequate soil water for winter wheat was from booting through grain-filling stage, while Eck (1988) reported that the critical period was during tillering and jointing. Hanks and Rasmussen (1982) reported that the critical stage for winter wheat in the US Great Plains was from heading to the soft-dough stage. In the North China Plain, Li (1992) and Zhang et al.

(1999) reported that the most critical stage was from stem elongation to milking.

Figure 11 shows the yield response to water stress at different growth stages in an experiment conducted at Luancheng Station from 1996 to 1999. Table 4 shows the sensitivity index of winter wheat to water stress at different growth stages, calculated using the method of Jensen (1968). A similar trend was observed by Li (1990) and Zhang et al. (1999b) that water stress at jointing caused the highest reduction in yield, followed by stress from booting to flowering, while the water deficit at turning green and maturing had no effect on crop yields. The highest value of λ_i appears at jointing stage and the negative λ_i value at turning green stage and maturing show that at these two stages moderate water stress is favourable for crop yield.

Tables 5, 6 and 7 show the results from different irrigation scheduling in the 1996–1997, 1997–1998 and 1998–1999 seasons. Rainfall was less than normal in all three years, and two irrigations applied at jointing stage and booting to flowering stages achieved higher yield and higher WUE than the fully irrigated treatments. In the 1997–1998 season, when the rainfall was

higher, a single irrigation at the jointing stage achieved the highest yield and highest WUE. The results showed that the conventional irrigation practice in the region does not produce the highest yield of winter wheat, and the WUE is also much lower. So it is necessary to re-schedule the irrigation based on the sensitivity index to water stress of winter wheat.
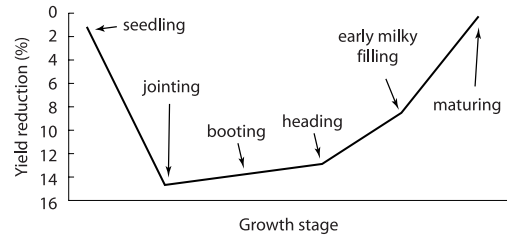
Figure 11. Yield reduction in winter wheat under water stress at different growth stages, Luancheng County, North China Plain, 1996–1999

The variation of sensitivity index among growth stages has practical implications for irrigation scheduling. Crop yield depends not only on the amount of irrigation water but also on water use during the
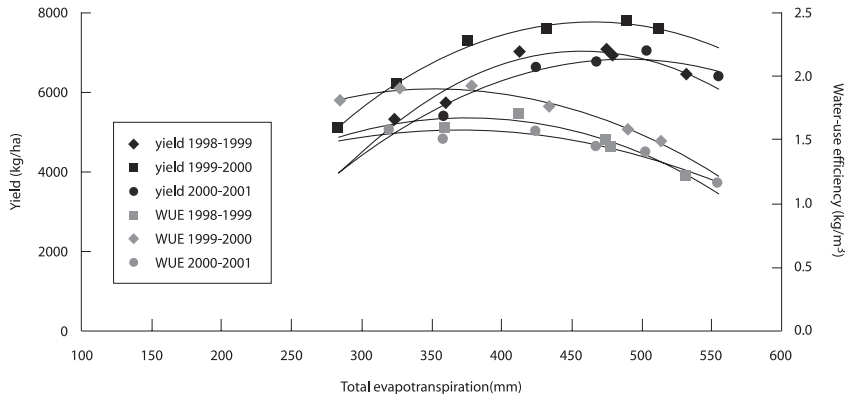
Figure 10. Relationship of water-use efficiency and yield of winter wheat to total evapotranspiration for three seasons at Luancheng Experimental Station on the North China Plain

Table 4. Sensitivity index (λ_i) of winter wheat to water stress at its various growth stages (Luancheng Experimental Station, North China Plain)

Growth stage	Turning green to start of noding	Jointing	Booting	Heading to early milky filling	Maturing
λ_i [a]	−0.1213	0.3145	0.2721	0.1016	−0.087
λ_i [b]	−0.09831	0.2823	0.201	0.1188	−0.0211

[a] Results from 1996–1997 experiments; [b] Results from 1988–1989 experiments.

growth stages. The limited water resources should be applied to the most sensitive stage to avoid stress. Irrigation scheduling should be adjusted according to climatic circumstances, especially rainfall patterns.

Critical soil water contents at various stages of winter wheat growth

Results from several studies suggest that, in many situations, about two-thirds of the extractable soil water can be used before the rate of photosynthesis falls (Turner 1990). Therefore, irrigation to replace water lost from soil may not be necessary, because as long as soil moisture is above a critical level, decreases in soil moisture may not reduce yield significantly. Thus, it is very important to know the critical soil water level and irrigate accordingly to save water. Even if plants suffer a slight stress above the critical soil water level, crop yield is not affected.

Due to variation in sensitivity at different growth stages of winter wheat growth, critical soil moisture levels for different growth stages are different. For example, at jointing stage, the most sensitive stage to

water stress, when irrigation was postponed by 7 days (soil moisture for 0–50 cm decreased from 22.5% to 17.4% by volume), yield could fall by about 11%. At the maturing stage, on the other hand, when soil moisture fell to 16.5% by volume, no effect was found on yield in 1997. Table 8 gives the critical soil moisture levels at various stages of winter wheat by summing-up several years of experimental results at Luancheng Station. The critical soil moisture levels could be taken as an indicator for irrigation.

Suggested management practices for irrigation scheduling with moderate water stress

- Make sure the soil moisture is high enough for germination and emergence of winter wheat.
- Determine whether or not an irrigation event is needed before winter freezing (equivalent to 3 tillers) according to critical soil moisture level.
- An irrigation event is needed at jointing stage.
- Irrigation at the heading stage is determined by precipitation availability. This irrigation could be omitted if it is wet year.

Table 5. The effects of irrigation scheduling on winter wheat yield and water-use efficiency (WUE) in 1996–1997 (Luancheng Experimental Station, North China Plain) (the growing season rainfall was 87.5 mm)

Irrigation time (month-day)	Total irrigation (mm)	Total water consumption (mm)	Grain yield (kg/ha)	WUE (kg/mm.ha)
11-21	67.5	364.7	5500.6	15.08
11-21, 4-22	144.4	428.6	6900.8	16.10
11-21, 4-29	153.5	434.5	6164.3	14.19
11-21, 3-27, 4-22	171.4	428.9	6494.3	15.14
11-21, 3-27, 4-29	200.1	475.9	6308.6	13.26
11-21, 3-27, 5-7	186.7	460.0	6503.3	14.14
11-21, 3-27, 5-14	193.7	476.1	6219.8	13.06
11-21,4-18, 5-14	194.8	470.1	7170.0	15.25
11-21, 4-29, 5-22	176.7	413.2	6236.6	15.09
11-21, 3-27, 4-22, 5-14	252.5	474.7	6503.3	13.70

Table 6. The effects of irrigation scheduling on winter wheat yield and water-use efficiency (WUE) in 1997–1998 (Luancheng Experimental Station, North China Plain) (the growing season rainfall was 126.5 mm)

Irrigation time (month-day)	Total irrigation (mm)	Total water consumption (mm)	Grain yield (kg/ha)	WUE (kg/mm.ha)
Non irrigation	0.0	299.4	5413.8	18.08
3-25, 4-21	95.0	338.4	5954.9	17.60
3-25, 5-20	151.3	366.0	5958.0	16.28
4-15	84.7	333.7	6088.2	18.24
3-25, 4-21, 5-20	175.9	375.6	5650.7	15.04
4-7, 4-21, 5-20	166.6	389.8	6066.0	15.56

Using these guidelines, irrigation events can be reduced from 3 or 5 to only 2 or 1, which amounts to a 50% saving in groundwater. Yield of winter wheat and WUE can be increased by 10% and 15–20%, respectively. If the results are similar for other counties in the NCP, and if these guidelines are applied over the entire NCP, then this means that much water will be saved, and that the agricultural systems may be sustainable for longer.

Adopting reduced tillage and mulching to reduce soil evaporation

Previous studies have shown that soil evaporation (E) varied from 80% to 15% of evapotranspiration (ET) during crop-growth seasons (Villalobos and Fereres 1990; Denmead et al. 1996; Daamen et al. 1993). A large quantity of soil moisture may be lost through evaporation, which can be reduced through good management practices (Fischer and Turner 1978). Most traditional tillage methods — for example, harrowing frozen soil in early spring — were effective in reducing soil evaporation. With no-till or reduced-till technology used, field mulching proved to be an effective measure for reducing non-productive water loss in soil and increasing WUE.

Figure 12 shows the E and ET of winter wheat during the 1995–1996 season, measured using the large-scale weighing lysimeter combined with a micro-lysimeter at Luancheng Station. The results showed that about one-third of the total ET was E. The percentage of E over ET was similar for other crops (Table 9). For the main cropping rotation of winter wheat–summer maize in this region, a total of 250 mm of soil water is lost as E annually, which equals the water applied in three irrigation events. If E could be reduced by 30%, WUE of crops will be increased and one or two irrigation events could be omitted. This could have great impact on easing the water overdraft problem in this area.

The results of field experiments over 12 years showed that applying mulch to maize using straw from winter wheat could improve WUE of maize by 7–10% (Figure 13) at Luancheng Station. The 7–10% increase in WUE equals 40–50 mm water saved, which is about one third of the total soil evaporation.

Table 7. The effects of irrigation scheduling on winter wheat yield and water-use efficiency (WUE) in 1998–1999 (Luancheng Experimental Station, North China Plain) (the growing season rainfall was 60.4 mm)

Irrigation time (month–day)	Total irrigation (mm)	Total water consumption (mm)	Grain yield (kg/ha)	WUE (kg/mm.ha)
Non-irrigation	0	323.0	5325.8	16.49
3-16	80	366.4	7023.8	19.17
4-3	80	338.2	6697.5	19.79
4-24	80	370.4	7058.3	19.06
3-4, 4-24	160	444.2	7592.0	17.09
3-11, 4-24	160	438.4	7422.5	16.93
3-17, 5-6	160	399.0	6915.0	17.33
3-17, 5-14	160	403.9	7344.6	18.18
11-2, 14-24	160	400.3	6923.0	17.29
3-31, 5-5	160	442.5	7296.0	16.49
11-21, 3-31, 4-24, 5-5	240	478.5	6937.5	14.51

Table 8. The critical soil moisture level (lower limit) for winter wheat at its various growth stages (Luancheng Experimental Station, North China Plain, 1997)

Growth stage	Seedling	Turning green to start of noding	Jointing	Booting	Heading to early milky filling	Maturing
Percentage of field capacity	60	55	65	60	60	50
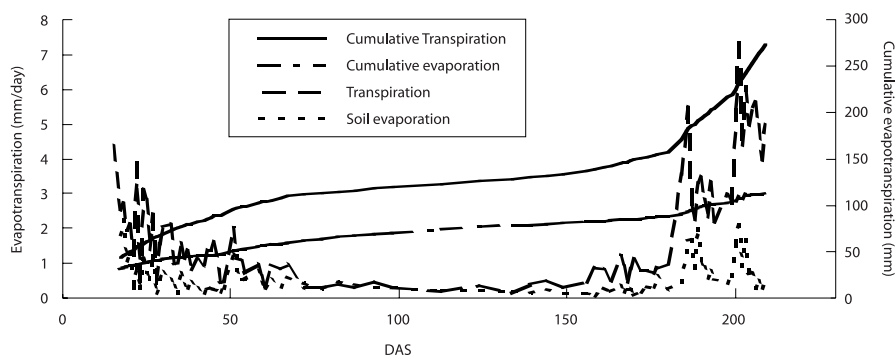
Figure 12. Daily and accumulated evapotranspiration and soil evaporation of winter wheat measured by large-scale weighing lysimeter and micro-lysimeter during 1995–1996 at Luancheng Experimental Station on the North China Plain

Mulching had already been applied to an area of 3.33 million ha in 1991 in China, according to a report from the Haihe Water Conservancy Commission (Haihe Hydraulic Commission, Ministry of Water Resources 1991). But it is difficult to apply mulching during the winter wheat growth period. The problems include lack of suitable machinery, low temperatures of soil in early spring, and decreased yield. We are integrating and demonstrating a no-till system with all-year mulching combined with new machinery and low-temperature-tolerant winter wheat cultivars.

Adopting higher WUE cultivars

There is a potential to improve the WUE by cultivar breeding and molecular biology (Richards et al. 1993). The responses of different crops or cultivars to water stress differ significantly and can result in improvements of up to 30% in WUE (Shan and Zhang 1999),

which implies that we could plant higher WUE cultivars. We conducted field experiments to compare the WUE of several winter wheat cultivars commonly used by farmers at Luancheng Station. The results showed that the differences in yield among cultivars is up to 10–15% and in WUE 10–20% (Figure 14). It is an easy and economical way to select higher WUE crops cultivars to improve the WUE. As shown in Figure 14, 'SX733' performed better in terms of both yield and WUE.

Possible effects of agronomic water-saving measures on groundwater table declining rate

The results showed that it was possible to reduce water use without affecting grain production in farmland by adopting optimised irrigation scheduling, applying straw mulching and selecting higher WUE

Table 9. The percentage of soil evaporation over the total evapotranspiration for different crops (Luancheng Experimental Station, North China Plain, 1998)

Crops	Total evapotranspiration (ET) (mm)	Soil evaporation (E) (mm)	E over ET (%)
Winter wheat	461.8	137.4	29.8
Maize	364.6	114.5	31.4
Cotton	519.6	141.8	27.3
Soybean	328.1	77.8	23.7
Millet	319.7	73.1	22.8
Sorghum	235.5	86.4	36.7

Note: Soil evaporation was measured by micro-lysimeter. Except for winter wheat and cotton, all other crops were planted in summer. Cotton was planted in spring

cultivars. The water-saving effects of those measures could reduce the rate of groundwater table decline by 80% calculated by the FEFLOW modelling in Luancheng County (Figure 15). Figure 15 shows that adopting all these water-saving measures could keep the groundwater level steady, avoiding significant falls. But without application of those measures, the groundwater table would drop quickly and, in about 20 years, the water level could be near sea level.
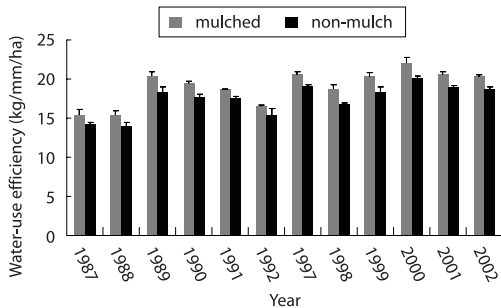
Figure 13. Comparison of water-use efficiency in maize with and without mulching for 12 seasons at Luancheng Experimental Station on the North China Plain
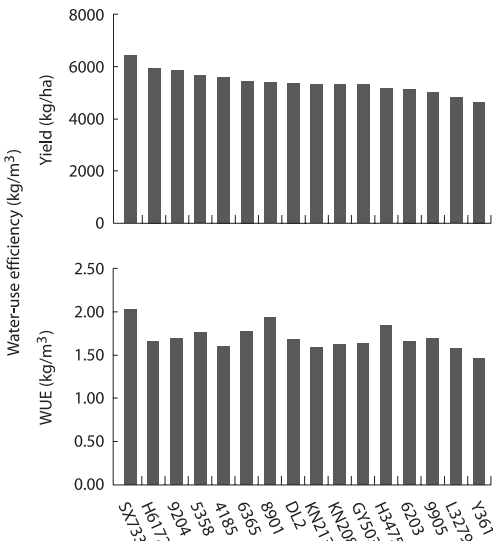
Figure 14. Yield and water-use efficiency for 16 winter wheat cultivars in the 2002–03 season at Luancheng Experimental Station on the North China Plain
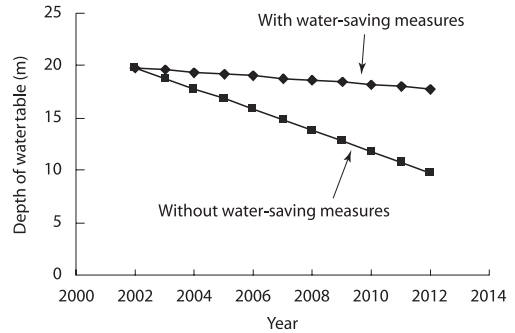
Figure 15. Groundwater water level change modelled using FEFLOW for Luancheng County under two conditions: the whole county adopting the water-saving measures and no adoption of such measures.

Conclusions

The main reasons for the watertable declining in the piedmont plain of Mt Taihang, in the northern part of the North China Plain, are related to the climate becoming warmer and rainfall decreasing, as well as human activities, reducing recharge from the mountain area to the plain. The low and variable precipitation cannot meet water requirements for the dominant cropping system of winter wheat and summer maize (two crops in one year). Groundwater is being over-exploited to meet the deficiency of water for high yield productivity. With expansion of the winter wheat planting area, the rate of groundwater table decline has increased. Because of the over-exploitation of groundwater, this cropping system is not sustainable. It is estimated that the shallow aquifer in the groundwater irrigation district of the piedmont plain of Mt Taihang will be completely depleted within 20–30 years. It is necessary to develop water-saving agriculture for sustainable use of groundwater resources to improve sustainability of regional agriculture.

Based on long-term field experiments and monitoring, as well as regional extension, some key measures have proved to be effective to reduce irrigation water use and to slow groundwater resources depletion. These include establishing rational farming systems matched to climate and water resources, establishing rational irrigation scheduling with moderate water-stress, adopting no-till technology to reduce soil evaporation, adopting higher WUE culti-

vars and adopting advanced irrigation techniques. These techniques have significant potential of water saving. Comprehensive integration and extensive extension of water-saving technology will greatly help overcome the situation of groundwater resources depletion.

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Conservation management of water and nitrogen in the North China Plain using a GIS-based water and nitrogen management model and agricultural decision support tool

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Abstract

Irrigation and fertiliser use have contributed to the success of food production in China, particularly in the North China Plain (NCP) which is an important grain production base for the country. However, there has been growing concern about the environmental implications of the high levels of input use. A large collaborative research project, 'Water and nitrogen management to increase agricultural production and improve environmental quality', was designed to investigate the efficiency and the environmental impact of traditional rates of nitrogen (N) and water use in wheat–maize production on NCP.

Comprehensive field measurements were conducted to quantify all essential water and N fluxes in one hectare plots at three locations in the NCP, in Fengqiu, Luancheng and Quzhou counties. A spatially referenced and process-based biophysical model, water and N management model (WNMM), was developed for the NCP. WNMM successfully simulated key water, carbon (C) and N dynamics, crop growth and agricultural management practices. The combination of field measurements and modelling showed excessive use of irrigation and N fertiliser. The water loss through deep drainage accounted for up to 30% of applied irrigation. There was about 25% N surplus in soil even after allowing for all the losses. Ammonia (NH_3) volatilisation was the main pathway of N loss if the fertiliser was surface broadcast in this high pH soil, and up to 48% of applied urea (96 kg N/ha) was lost within two days after application to summer maize. Deep placement or broadcast followed by immediate irrigation reduced NH_3 volatilisation by 75%. Nitrate leaching ranged from 12 to 82 kg N/ha (3–16% applied N). Denitrification was less significant in the sandy soil, accounting for less that 10%, but about 50% of that was nitrous oxide (N_2O).

Based on WNMM and farmer surveys, a geographical information system based agricultural decision support tool (ADST) was developed for optimum irrigation and fertiliser use. The ADST facilitated the adoption of better management practices, particularly in terms of fertiliser management. The project resulted in annual reductions in fertiliser use of around 20–23% and annual cost savings from reduced water pumping costs of $10–45 per ha, with yield increases ranging from no change to 4% per year. For an average-size farm, input costs fell by 12–18%, equivalent to an increase in income of $50–109 per year. An impact assessment study estimated the net benefits attributable to the project at A\$216.2 million

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中国华北平原农田水氮优化管理
－基于GIS支持下的水氮管理模型（WNMM）和农业决策支持工具（ADST）

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摘要：华北平原是中国重要的粮食作物生产基地，灌溉和施肥对粮增加食产量发挥了重要作用。农业生产中灌溉和施肥的高投入导致的环境影响已越来越引起人们重视。中澳合作项目"水、氮管理以增加农业生产和提高环境质量"在华北平原小麦——玉米轮作区开展了农田水氮管理及其环境效应方面的研究。

在华北平原封丘、栾城和曲周县的1公顷试验地内，开展了农田水、氮通量的综合观测，并建立了GIS支持下的水氮管理模型（WNMM）。WNMM能对水、碳和氮动态、作物生长及农田管理进行了空间和过程的分析与模拟。田间观测和模型模拟的综合结果表明，该地区灌溉用水量和氮肥施用量均存在过量现象。灌溉用水损失率达 30%以上，扣除肥料损失后土壤中仍有约 25%的氮量冗余。在这种高PH值土壤上，氮肥表施后主要的氮损失途径是氨氮挥发，夏玉米地施尿素肥2天内氮素损失达 48%以上（约 96kg N/ha）， 深施或施肥后即灌溉可使氨氮挥发损失量减少75%。氮淋溶下渗量在 12－82kg N/ha之间，占施氮量的 3－16%。在沙质土农田，反硝化作用不明显，氮损失量小于10%，但其中50%的氮损失以N_2O的形式排放。

在田间调查和 WNMM 模型的基础上，建立了 GIS 基础上的灌溉和施肥的农业决策支持工具（ADST）。ADST 促进了农田管理尤其是化肥施用管理的优化措施推广和应用。研究结果的应用使得研究区域年均化肥施用量减少 20-23%，灌溉减少节约投入资金每公顷达 10-45 澳元，作物年度增产 4%。单位农田的投入减少 12-18%，相当于农民每年收入增加 50-109 澳元。项目经济效益评估为 2.16 亿澳元。

关键词：水氮动态，灌溉，氮肥管理，农业决策支持系统，GIS，WNMM

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Introduction

Irrigated agriculture has long been considered to guarantee national food security in China. The irrigation area covers 45% of the total cropland and produces nearly 80% of total grain (Wang 2005). However, crop production is often limited by the availability of nitrogen (N), especially in irrigated cropping. Much of the progress in food production has resulted from the rapid increase in use of chemical N fertiliser, and there is a good correlation between food production and fertiliser consumption from 1970 through to the 1990s (Zhu and Chen 2002). There is, nevertheless, ample evidence of excessive use of water and fertiliser in China which not only exacerbates the water shortage but has also resulted in nitrate (NO_3^-) pollution to groundwater and water bodies (Norse and Zhu 2004; Chen et al. 2005). One of the main areas of food production in China is the Huang-Huai-Hai (HHH) Plain, or North China Plain (NCP) of this study, where crop yields have increased dramatically from a low base through intensification of management over the past 20 years. Evidence from the NCP indicates that, with increased use of irrigation water and N fertiliser inputs of up to 500 kg N/ha/year to produce grain yields of about 10 t/ha/year, the groundwater resources have been over-exploited and NO_3^- concentrations in groundwater have risen to above 50 mg NO_3–N/L. High rates of N fertiliser and inappropriate irrigation practices have also led to increased emission of the greenhouse gas nitrous oxide (N_2O), and agricultural emissions account for more than 60% of the total N_2O emissions in China (Zheng et al. 2004).

It has been recognised by scientists and policy-makers in China that a sustainable, high-production agricultural system cannot be achieved at the expense of environmental quality and scarce water resource. Better management practices, with more efficient use of water and N fertilisers, balancing both economic and environmental interests are required. This is a challenging task because it requires a comprehensive understanding of the dynamics of water and N in plant–soil systems, the impact of soil and environmental variables and management practices on these dynamics, and socioeconomic constraints. The system modelling approach is one of the most appropriate techniques for such a complex task. Process-based simulation models, which describe in sufficient detail the dynamics of water and N in the atmosphere–soil–crop system, can be of great assistance in understanding the interactions between different processes.

They can also be used to identify gaps in our knowledge and help in designing experiments that aim to clarify poorly understood parts of the system. The use of simulation models for identifying best management practices (BMPs) for agriculture has also been significantly improved in recent decades.

Computer models can be categorised as either lumped or spatial parameter models, depending on the kind of parameters required. A lumped model is one in which processes are modelled within a system of discrete spatial objects, and the model solution describes the input and output of each object without attempting to determine the precise spatial distribution of the processes within the object. In the United States and Europe, there are a number of published and widely used lumped models simulating soil water dynamics, C and N turnover and crop growth: NLEAP (Shaffer et al. 1991), RZWQM (Ahuja et al. 2000), CENTURY (Parton et al. 1994), GLEAMS (Knisel, 1993), NCSOIL (Molina et al. 1983), EPIC (Williams 1995), DNDC (Li et al. 1992), SOILN (Johnsson et al. 1987), DAISY (Hansen et al. 1991), and SUNDIAL (Bradbury et al. 1993). All these models consider the main soil N dynamic processes, namely fertiliser N application, mineralisation, immobilisation, nitrification, denitrification and, in a few cases, N_2O emission, NH_3 volatilisation, NO_3^- leaching, and crop N uptake. Whilst these models have achieved various degrees of success in application, they all are site-specific, and use lumped parameters.

Spatial models, on the other hand, run over a continuous space in which the solution is determined for each spatial element. There are a few published spatial simulation models of agro-ecosystems, namely AGNPS (Young et al. 1987), SWRRB-WQ (Arnold et al. 1990), SWAT (Arnold et al. 1993), ANSWERS-2000 (Bouraoui and Dillaha 1996), and ecosys (Grant 2001). These models allow users to evaluate alternative practices and scenarios in large agro-ecosystems. They have limitations when applied, however, including: the empirical expressions for soil water dynamics and C and N transformations; the large input data requirements; parameters that are difficult to estimate or to obtain; uncertainty in inputs; and a lack of technical support to understand or interpret the tremendous amount of simulation outputs. Recently, researchers have successfully integrated mathematical simulation models with spatial-referenced database systems like GIS and expert systems to significantly reduce the time and labour required to run the models, and to graph-

ically visualise the simulation outputs (Arnold and Sammons 1989; Heatwole 1990; Srinivasan and Arnold 1993).

The main objective in the recently completed ACIAR project, 'Water and nitrogen management to increase agricultural production and improve environmental quality' (LWR1/1996/164), was to achieve improved water and nutrient management for crops in the NCP. The project consisted of three major components: (a) comprehensive field measurements to quantify all essential water and N fluxes; (b) development of a spatially referenced and process based biophysical, water and N management model (WNMM); and (c) development of a user friendly and GIS-based agricultural decision support tool (ADST) to assist policymakers and farmers identify strategies to improve farm productivity and regional environmental outcomes in the NCP.

Research methods

The project was a mix of detailed experimental measurement, collection of relevant resource data, development of process models, and integration of the models with a GIS containing spatial data so that model outputs can be expressed spatially at appropriate scales. The project comprised three subprojects: (1) quantifying water and N losses from the soil-plant systems to the environment; (2) systems modelling for crop, water and N management; and (3) information dissemination and policy advice.

Field experiments

The project was carried out in three counties, representing major soil types in the NCP supporting intensively managed irrigated wheat–maize cropping systems; Fengqiu County in Henan Province and Quzhou and Luancheng counties in Hebei Province.

One 1 ha (100 × 100 m) experimental plot located in each of the three counties was set up on experimental stations associated with the Chinese Academy of Sciences (Fengqiu and Laucheng) and the China Agricultural University (Quzhou) to carry out the detailed field measurements to quantify the water and N dynamics in the irrigated wheat and maize systems, and to parameterise the WNMM model. The following water and N losses from soil–plant systems to the environment were measured:

- water drainage losses below the root zone
- NO_3^- leaching below the root zone

- NH_3 volatilisation
- denitrification and greenhouse gas (N_2O) emissions.

The soil in the region is generally classified as a moderately well drained loam (Ustic Luvisol), with soil organic matter around 10 g/kg, total N around 1.0 g/kg, and pH of 8.0–8.5 (1:5 H_2O). All detailed field design and measurement methods are described in the experiment and data collection protocol (White et al. 1998).

Development of water and nitrogen management model (WNMM)

WNMM is a process-based model. It simulates key processes of water and C and N dynamics in the surface and subsurface of soils during the crop growth period.

- **Water dynamics**

WNMM was designed to simulate the hydrology of the soil–crop system described in Figure 1. It includes potential evapotranspiration, soil evaporation and plant transpiration, dynamic soil water content and flux, NO_3^-, NH_3 and urea transport, and soil temperature at depth.

- **Carbon and nitrogen cycling**

WNMM simulates N transformations in the agroecosystems, including mineralisation of fresh crop residue N and soil organic N, formation of soil organic N, immobilisation in biomass, nitrification, NH_3 volatilisation, and denitrification as well as N_2O emissions (see Figure 2). It divides soil C into three pools: fresh residue C, microbial biomass C (living and dead), and humus C (active and passive in terms of mineralisation).

- **Crop growth**

The crop growth module in WNMM was used to predict total crop dry matter, leaf area index, root depth and density distribution, harvest index, crop yield, and N uptake.

- **Agricultural practices**

WNMM simulations include consideration of the agricultural management practices such as crop rotation, tillage and stubble return, irrigation, and N fertiliser applications.

Finally, the process model was fully integrated into GIS by using a uniform data structure, ARC GRID ASCII format, which can be fully operated both in the GIS environment and in this process model.

Development of an agricultural decision support tool (ADST)

Based on WNMM, a spatially referenced agricultural decision support tool (ADST) was developed for optimal water and fertiliser management. This involved simulating a large number of management scenarios using WNMM and assessing BMPs against selected criteria. The selected criteria were expressed with the following indicators: crop yield, irrigation water-use efficiency (IWUE), fertiliser-use efficiency (FUE), net N leaching, N_2O emission and total regional water use for agriculture. It should be noted that the objective 'to alleviate over-exploitation of water resources' is difficult to quantify, therefore the indicator 'total regional water use for agriculture' is adopted instead. Groundwater is the main water source for irrigation in the area.

Results and applications

Field experiments

• *Drainage losses below the root zone*

Considerable deep (out of root zone) drainage occurred under the current agricultural practices (Table 1). Most of the loss occurred in the summer maize-growing season, except in the 1998–1999 season at the Quzhou site. Drainage was lowest at Luancheng, 34–87 mm year^{-1}, and much higher at Fengqiu and Quzhou, 116–274 mm, accounting for around 60% of total irrigation at the Fengqiu site in 1999–2000. Such high drainage, even in the dry year 1998–1999, indicated that the irrigation amount was excessive. The county survey data showed there is no clear correlation between the irrigation amount and maize yield. There is large potential to reduce the irrigation and improve the efficiency of irrigation water use.
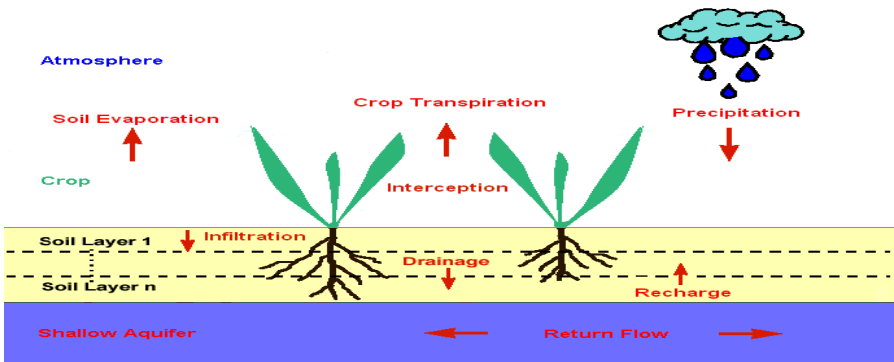

Figure 1. Conceptual diagram of water balance in soil–crop system in the water and nitrogen management model
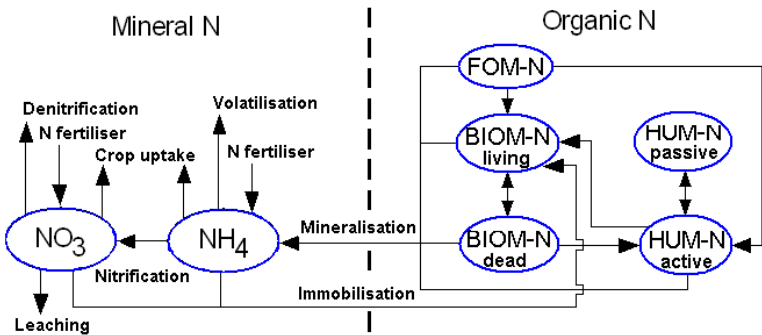

Figure 2. Conceptual diagram of nitrogen cycling in soil–crop system in the water and nitrogen management model

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- *Nitrate leaching below the root zone*

For the first time in China, actual NO_3^- leaching was systematically measured and simulated. In the 1 ha experimental sites, the average accumulated NO_3^- leaching for the complete wheat–maize crops ranged from 12 to 49 kg N/ha, accounting for 3–11% of applied N in 1998–1999, and 21–82 kg N/ha in 1999–2000, accounting for 4% and 16% of applied N (Table 2). This significant N leaching was caused by the excessive N fertiliser application, 412–502 kg N/ha, and inappropriate and excessive irrigation as discussed above. This is not only a financial loss for the farmers, but also a serious environmental issue because the nitrate is very stable when it is leached below the root zone and will accumulate in the groundwater. Apparently, the N leaching varies greatly among the three locations and between two rotations years. This compares with the unconfirmed N leaching benchmark of 35 kg N/ha/year for arable land in China suggested by Li and Zhang (1999). The groundwater system under the Fengqiu site was more likely to be contaminated by the leached nitrate because of the high groundwater table (less than 5 m and mostly around 2 m).

- *Ammonia volatilisation*

Using the micrometeorological method (Denmead 1983) at Fengqiu, the research team identified that NH_3 volatilisation was the main pathway of fertiliser N loss in this high pH soil when it was applied by the traditional method of surface broadcasting (Zhang et al. 2004). Ammonia volatilisation commenced very rapidly. The flux density reached a peak within 24 hours and fell to a low value 2 days after application (Cai et al. 2003). The losses accounted for 44–48% of the applied N for urea applied to maize at sowing in 1998 with direct surface broadcasting (Table 3). The losses were reduced to 18% when urea was applied by surface broadcasting followed by irrigation, and to 11% when urea was applied by deep placement (Table 3). In contrast, there were significant NH_3 losses, 42–60 kg N/ha accounting for 27–34% of applied N, when urea or ammonium bicarbonate was applied (surface broadcasting followed by the irrigation) to maize at the Luancheng and Quzhou sites. Apparently, surface broadcasting followed by irrigation reduced NH_3 volatilisation, but it was not as effective as deep placement or incorporation. The NH_3 loss from N applied to wheat crops was much less than from the maize, due to the low temperature and the effective incorporation method (Cai et al. 2002a,b).

Table 1. Summary of drainage estimated by dynamic process simulation models at three 1 ha sites in China

Site	Period	Precipitation (mm)	Irrigation (mm)	Evapotranspiration (mm)	Drainage (mm)
Fengqiu	1/10/98–30/9/99 1/10/99–30/9/00	307 655	571 452	892 849	101 220
Luancheng	1/10/98–30/9/99 1/10/99–30/9/00	347 402	483 452	788 840	34 87
Quzhou	1/10/98–30/9/99 1/10/99–30/9/00[3]	280 490	675 475	723 828	228 226

Table 2. Nitrate leaching loss at three experimentation sites in the wheat and maize rotations of 1998–1999 and 1999–2000

Period	Site	N applied (kg N/ha)	Nitrate leaching (kg N/ha)	Percentage of applied N
1/10/1998–30/9/1999	Fengqiu Luancheng Quzhou	466 418 445	29 12 49	6 3 11
1/10/1999–30/9/2000	Fengqiu Luancheng Quzhou	502 412 490	82 61 21	16 15 4

- ***Denitrification and greenhouse gas (nitrous oxide) emissions.***

Denitrification loss was much less significant than NH_3 volatilisation. An exception was the large denitrification loss, 22 kg N/ha accounting for 11% of applied N, observed in the field experiment with maize at Fengqiu in July 1998 (Cai et al. 2003). The measured total denitrification losses were only about 5% of the N applied. Like the NH_3 volatilisation, the peak denitrification was mainly in July and August, after the events of N fertiliser application and irrigation/rainfall. N_2O emission accounted for more than 50% of total $N_2O + N_2$ losses when conditions did not favour denitrification, indicating that the nitrification process contributed to the total losses. However, it is always a challenge to quantify the denitrification process in the field because it is very dynamic and affected by many soil parameters, especially the soil water content and available C supply. With the method used (the acetylene inhibition technique), the peaks of denitrification may have been missed because the field was not accessible to carry out the measurement immediately after the rainfall

and irrigation, which was evident in the WNMM modelling (Chen et al. 2002; Li et al. 2005). Although N_2O emissions and denitrification are not very important in the N economy in this well-drained soil, it is an environmental concern because N_2O is a potent greenhouse gas, especially given the high ratios of $N_2O/(N_2 + N_2O)$ observed.

- ***Total N balance***

The total N budget for the 1 ha experimental plot at Fengqiu for 1988–1999 maize–wheat rotation is summarised in Table 4. The groundwater N supply was estimated by the NO_3^- concentration in the groundwater and upward soil water fluxes to the root zone (Li 2002). The input by crop residues was an estimation because the losses of crop residue N were not measured. The best practices of N fertiliser application were adopted in this field site. The urea was applied either by deep placement (wheat) or surface broadcasting immediately followed by the irrigation (maize). Therefore, the NH_3 volatilisation was very low, accounting for less than 10% of applied N. After considering all the inputs and outputs of N, there is considerable N surplus in the system; 118 kg/ha

Table 3. Ammonia volatilisation (kg N/ha) from the N fertilisers applied to maize/wheat at the three experimental sites

Year	Crop	Site	Application method	Ammonia volatilisation	Percentage of applied N
July 1998	Maize	Fengqiu	SB[a]	44–96	44–48
June 1998	Maize	Fengqiu	BI[b]	13	18
July 1998	Maize	Fengqiu	DP[c]	22	11
July 1999	Maize	Luancheng	BI	42	27
Oct 1999	Wheat	Luancheng	Incorporation	1.2	1
Mar–Apr 2000	Wheat	Luancheng	BI	17	16
July 1999	Maize	Quzhou	BI	60	34
Oct 1999	Wheat	Quzhou	Incorporation	1.2	1
Aug–Oct 2000	Wheat	Quzhou[d]	BI	47	24

[a] Surface broadcast; [b] Broadcast followed by irrigation; [c] Deep point placement; [d] Ammonium bicarbonate was applied.

Table 4. N balance in the 1 ha experiment plot in 1998–1999 maize–wheat rotation at Fengqiu (kg N/ha)

Input		Output	
Fertiliser	466	Grain removal	389
Irrigation + rain	25	NO_3^- leaching	29
Groundwater	15	NH_3 volatilisation	35
Crop residue (estimated)	90	Denitrification + N_2O	25
Sub-total (A)	596	Sub-total (B)	478
Total N balance (A–B)		118	

accounting for 25% of total N applied. The excessive application of N fertiliser is very common in China and is a principal cause for non-point pollution there (Norse and Zhu 2004; Wei et al. 2005). The excessive application of N was consistent also with the observations of a significant accumulation of NO_3^- in the deeper soil (6–10 m) layers in cropping sites in Beijing (unpublished data). It is also evident that soil organic N has been increasing significantly in many irrigated soils in the NCP over last three decades (unpublished data).

Developing and calibrating the WNMM

The WNMM ran at a daily time step at different scales, driven by lumped variables (climatic data and crop biological data) in text data format and spatial variables (soil and agricultural practices) in ARC GRID ASCII format data. In this section, some results simulated by WNMM against the field observed data at the site scale and at the county scale in Fengqiu County are presented. There was good agreement between the WNMM simulation results and the field in-situ measurements of soil water, evapotranspiration, leaf area index, and NH_3 volatilisation carried out from 1 October 1998 to 30 September 2000, including two winter wheat and summer maize growing seasons (Figure 3).

WNMM was then applied to three scenarios to simulate the effect of different irrigation and N fertiliser management strategies on the key biophysical processes at the county level. The three scenarios were: the raw survey result, the survey-summarised result based on the actual agricultural practices in the whole county (called hereinafter 'actual scenario'), and the optimal result derived from the WNMM by 'what-if' scenarios. Comparing the output with the survey and survey-summarised scenarios, the optimal scenario showed the potential for savings of 100 kg N/ha/year of N fertiliser (22% reduction) and 200 mm irrigation water (44% reduction) per year (Figures 4 and 5). There were also significant environmental benefits due to reductions in N losses due to leaching, volatilisation and denitrification.

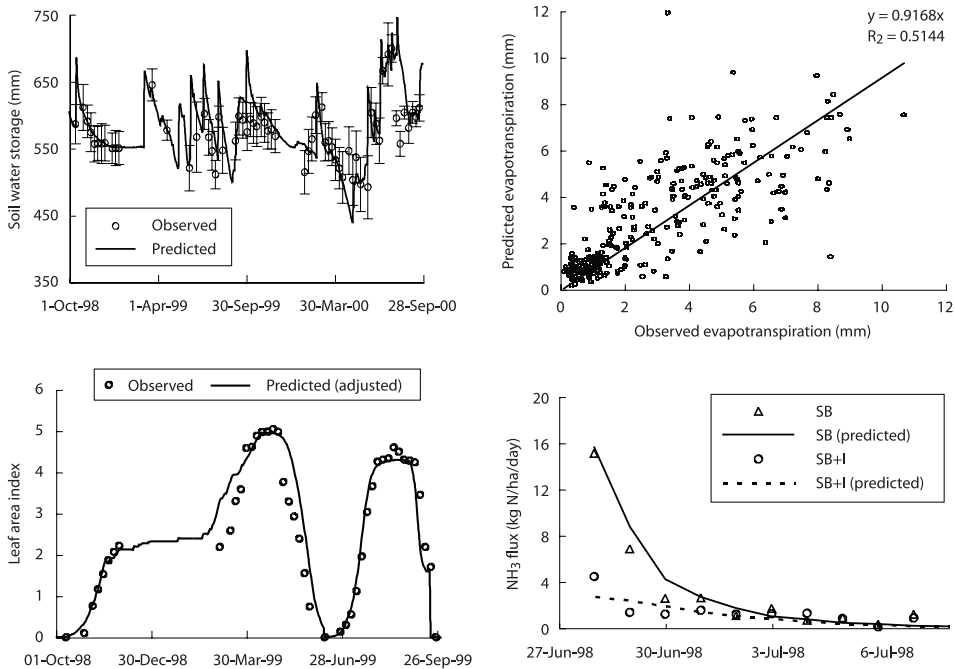**Figure 3.** Water and nitrogen management model simulations versus the observed data of soil water storage (top 170 cm) (top left), actual evapotranspiration (top right), crop leaf index (bottom left), and ammonia volatilisation (bottom right) in the 1 ha experiment plot of Fengqiu County, Henan Province, China (SB denotes surface broadcasting method, SB+I surface broadcasting immediately followed by irrigation) (Chen et al. 2005)

Development of a GIS-based agricultural decision support tool (ADST)

Based on WNMM, a user-friendly agricultural decision support tool (ADST, Figure 6) was developed for estimating optimal water and fertiliser management for the three counties. This involves simulating a large number of scenarios using WNMM and selecting BMPs based on pre-determined valuation criteria. The valuation criteria consider the crop yield, efficiency of irrigation water and N fertilisers and environmental impacts, NO_3^- leaching and N_2O emissions. Nominal weighting factors were allocated to each of above criteria. The ESRI MapObjects GIS component was used to manage the relevant spatial databases. The ADST is a GIS-based map display tool with a number of search/query functions for seeking site-specific BMPs (Figure 6).

Applications of ADST

Compared with the practices current at the time, the BMPs in the ADST would result in savings of 115 kg N/ha/year fertiliser N (26% less) and 150 mm irrigation water (33% less) per year while maintaining the crop yield similar to the current surveyed yield (Table 5). The IWUE and FNUE would increase by 32% and 20%, respectively. There were also significant environmental benefits: the net N leaching and N_2O emission fell by 60% and 25%, respectively. The total potential saving in irrigation water is 56 million m^3 for Fengqiu County (Table 5). This is of great significance to alleviate local water scarcity for the county as the potential water saving accounts for 13% of total water used for agriculture in Fengqiu County. Annual total water use is 459 million m^3 in which the water used for irrigation is about 420 million m^3 (Fengqiu County Water Resources Bureau 2004).

As for farm economic return, for an average-size farm, input costs fell by 12–18%, and the income per household would rise by 5% if the recommendations on fertiliser use and irrigation were fully adopted, equivalent to an increase in income of $50–109 per year. The net benefits attributed to the project were estimated at A$216.2 million (Harris 2004). This showed a significant poverty-reduction effect of the project.

Table 5. Comparison of simulation results between the current agricultural management practices and the best management practices provided by the agricultural decision-support tool (ADST) in Fengqiu County

Indicators	Current practices	Best management practices	
		Amount	Percentage change
Irrigation use amount (mm)	450	300	−33
Fertiliser use amount (kg/ha)	450	335	−26
Crop yield (kg/ha)	10,300	10,000	−3
Irrigation water-use efficiency (kg/ha/mm)	25	33	+32
Fertiliser N use efficiency (kg/kg N)	25	30	+20
Net N leaching (kg N/ha)	3.0	1.2	−60
N_2O emission	12	9	−25
Total water use for wheat–maize ('000,000 m^3)[a]	168	112	−33

[a] The cropping area is 37,150 ha for wheat–maize system. Total water use refers only to water used in the field and does not include the conveyance loss from the water sources to field.

Table 6. Project benefits in Fengqiu County at the completion year (2003–2004) (Harris 2004)

Cost–saving rate per household after adoption	12%	Increase rate in income per household	5%
Adoption rate for fertiliser use	55%	Cost saving from fertiliser use ('000 Yuan)	6048
Adoption rate for irrigation	10%	Cost saving form irrigation ('000 Yuan)	178
Total project benefit ('000 Yuan)	6226	Proportion of water saving in total regional water use	1.2%

Note: the cropping area is 37,150 ha for the wheat–maize system. The change in benefit from yield is assumed to be zero.
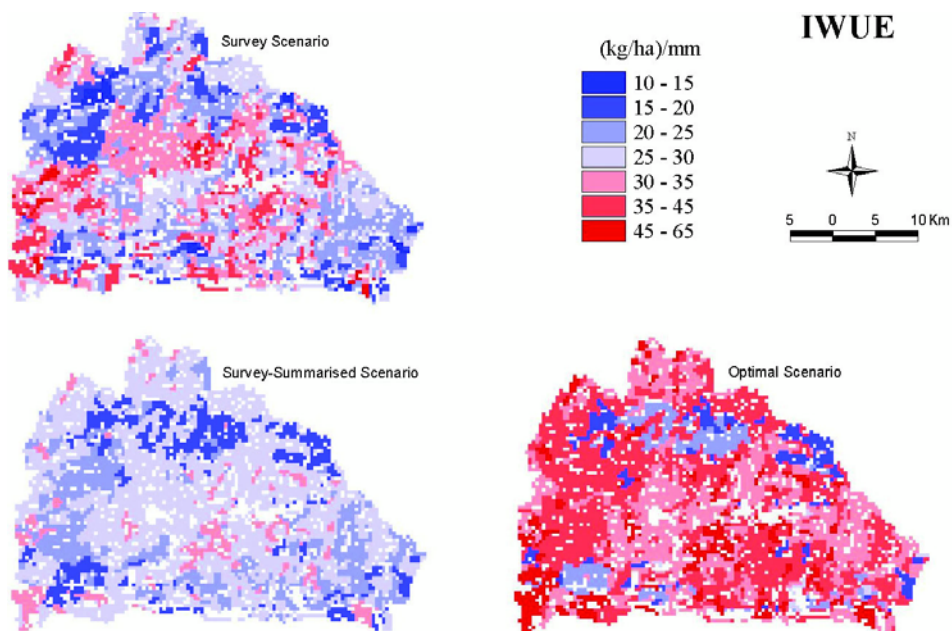
Figure 4. Predicted irrigation water use efficiency (IWUE) of three agricultural scenarios in Fengqiu County in 1998–1999 (Chen et al. 2002)
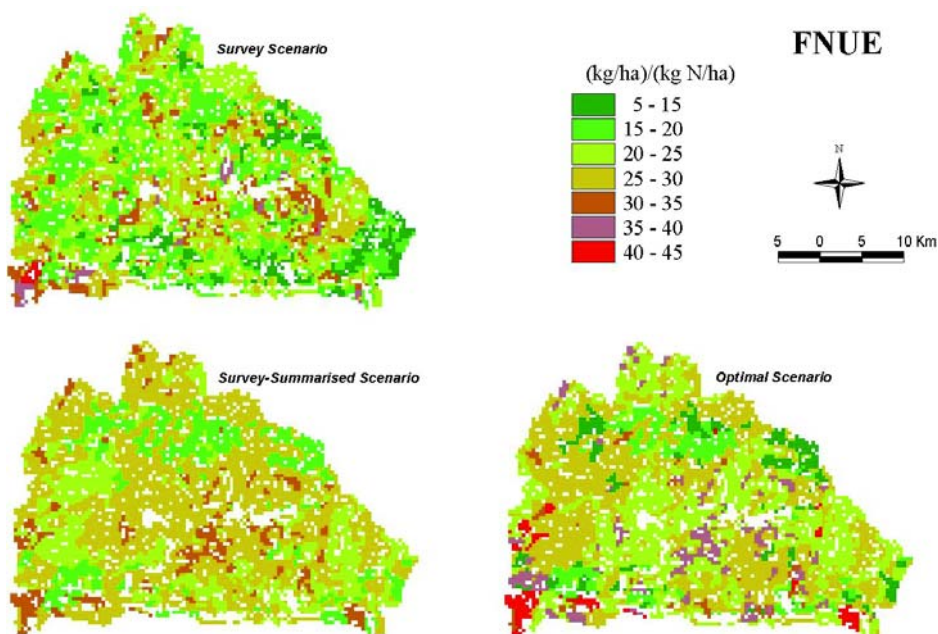
Figure 5. Predicted fertiliser N use efficiency (FNUE) of three agricultural scenarios in Fengqiu County in 1998–1999 (Chen et al. 2002)

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The ADST has significantly facilitated the adoption of the recommended practices. The actual project benefit in the year of the project completion is summarised in Table 6, extracted from the ACIAR project impact assessment report (Harris 2004). The adoption rate of fertiliser use advice was relatively high at 55%. The adoption of irrigation advice was much lower, only 10%. About 95% of total project benefit comes from the fertiliser saving and only 3% comes from the water saving. Apart from the low adoption rate, this is also attributed the low water price in Fengqiu County, as the cost of irrigation accounts for only 14% of total input cost while the cost of fertiliser accounts for up to 40% (Wei et al. 2006).

Conclusions and future directions

A spatially referenced and process-based biophysical model—the water and N management model (WNMM)—has been developed for the NCP. Both field measurements and modelling showed excessive use of irrigation and N fertiliser. There was about 25% N surplus in the soil even after allowing all the losses. Ammonia volatilisation was the main pathway of N losses if fertiliser was applied inappropriately. Nitrate leaching was as high as 82 kg N/ha. Although the denitrification was less significant in sandy soil, accounting for less than 10%, about 50% of that was as N_2O.

A GIS-based decision support (ADST) was developed for optimum irrigation and fertiliser use. The ADST significantly facilitated the adoption of BMPs, particularly in terms of fertiliser management practices.

Catchment-based management is more appropriate to the nature of river and groundwater resources than administrative-based management. Therefore, WNMM needs to be extended into a catchment-scale model or integrated with a 3D hydrological model. Climate variability, in particular the rainfall variation in different hydrological years, needs to be considered in the ADST. A more comprehensive socioeconomic component for WNMM needs to be developed to advise policymakers and farmers on how different agricultural practices influence farm profitability and environmental outcomes, and to simulate how different policy instruments might influence the agricultural practices.

Figure 6. A screen view from the agricultural decision-support tool (ADST) for Fengqiu County, Henan Province (Chen et al. 2002)

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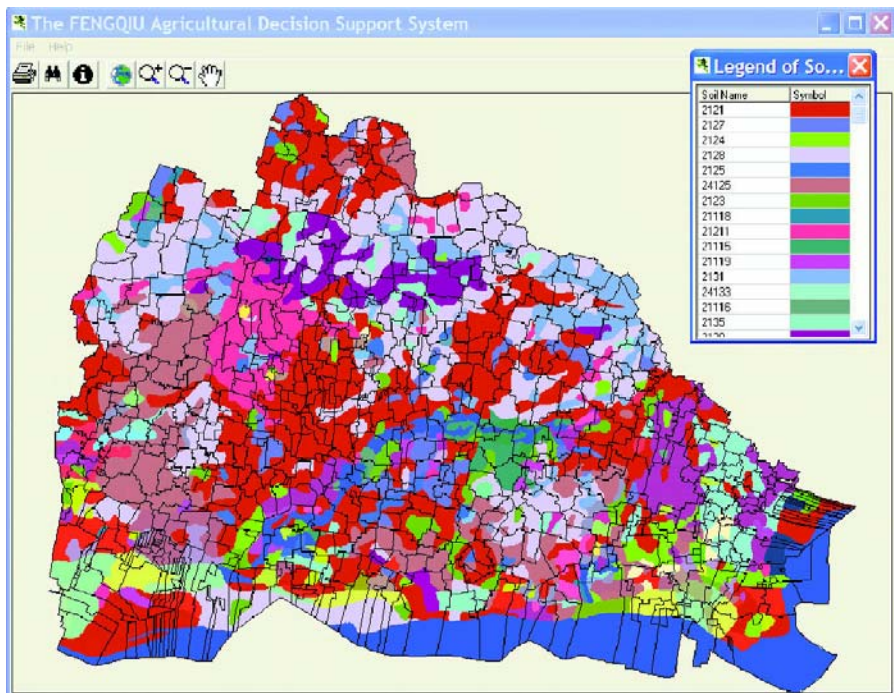Arnold, J.G., Engel B.A. and Srinivasan, R. 1993. A continuous time, grid cell watershed model. In: Proceedings of application of advanced information technologies for the management of natural resources. Chicago, Illinois, ASAE Publications, 267ñ278.

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Impacts of improved irrigation and drainage systems of the Yinchuan Plain, northern China

Riasat Ali[1] and Jiamin Wu[2]

Abstract

The Yinchuan Plain, located on the banks of the Yellow River, is historically one of the largest irrigation areas in northwestern China, having a large network of irrigation and drainage channels. Irrigation from the Yellow River over a long period has caused waterlogging, secondary salinity, shallow groundwater levels and environmental pollution. In addition, over-exploitation of deeper groundwater in some parts of the plain is causing groundwater pollution due to leakage from shallow unconfined aquifers. This paper summarises research to meet these problems.

The research project identified areas that are at high risk of salinity and shallow groundwater level development. The shallow groundwater is saline, and extensive areas of the Yinchuan Plain have medium soil salinity risk. There is widespread pollution of both surface and groundwater from nutrients and salts. Shallow groundwater in more than 50% of the Yinchuan Plain has been polluted. There is excessive seepage from irrigation channels to the surrounding land, resulting in the development of shallow watertables and soil salinity.

It was determined through field trials and geochemical modelling that up to 50% shallow groundwater can be mixed with surface water for irrigation without any significant losses in crop productivity. Reduction in crop yield is expected if groundwater alone is used for irrigation. Field experiments and modelling suggested that, by replacing flood irrigation with furrow irrigation, about 35% of the irrigation water can be saved without sacrificing productivity. Deep, open drains are effective for lowering the shallow watertables and reducing soil salinity. In some areas around Yinchuan city, the groundwater abstraction from the first confined aquifer should be reduced to avoid leakage and pollution from shallow groundwater. The surface water levels in Sand Lake should be lowered by 0.5 m to help arrest the spread of salinity in the surrounding areas.

Based on these research findings, investment plans for salinity management, surface water pollution control and irrigation and drainage management have been prepared by the local government and agencies. The local government has already installed 3000 shallow groundwater production wells in the region to help control shallow groundwater levels and supplement irrigation. The Yellow River water quota for the region has been reduced by about 30%.

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中国北方银川平原改善灌溉与排水系统的影响

摘要：银川平原坐落于黄河岸边，在历史上是中国西北部最大的灌区之一，银川平原拥有庞大的灌溉排水渠系网络。长时间的引黄灌溉引发了渍涝、次生盐碱化、地下水位高和环境污染等问题。此外，在该平原的某些地区超量抽取深层地下水引发了因浅层潜水渗漏而造成的地下水污染问题。这篇论文总结了这方面的研究成果。研究项目识辨出了盐碱化和地下水位上升危险程度高的区域。浅层地下水是咸水，银川平原的大面积范围有中度土壤盐碱化危险。大面积的地表水和地下水受到养分和盐的污染。银川平原50％以上的浅层地下水已经受到了污染。灌溉渠系向周边土地的渗漏量大，引发了地下水埋深浅和土壤盐碱化问题。通过田间试验和地质化学模型判定，有50％的浅层地下水可以与地表水混合后用于灌溉，且不会使作物产量受到大的影响。如果只用地下水灌溉作物，会造成作物减产。田间试验和模型结果建议，用沟灌代替漫灌可以节约35％的灌溉水量，且不会影响作物产量。深的明沟对降低浅层地下水位和减少盐碱化是有效的。在银川市的一些地方，应当减少从第一个承压水层提出地下水，以避免浅层地下水的渗漏和污染。沙湖的水位应当降低0.5米，以控制其周边地区盐碱化的扩散。在这些研究成果的基础上，当地政府和组织制定了盐碱化管理、地表水污染控制和灌溉排水管理的投资计划。当地政府已经在该区域建设了3000眼井抽取浅层地下水，以便控制地下水位并补充灌溉水源。黄河向该区域的供水配额已经减少了30％。
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Introduction

Ningxia Autonomous Region is located in the north-west of China and the Yinchuan Plain occupies its northern parts (Figure 1). It covers an area of approximately 7790 km^2. The Yinchuan Plain is surrounded by the Helan Mountains in the west and the E'erduosi highland in the east (Figure 2). The Yellow River enters the plain from the southwestern boundary and follows along its southern boundary to the east and continues northward. The plain slopes gently towards the east and north. The plain is approximately 165 km long and varies in width between 40 and 60 km. The predominant soil types are alluvial and Podzolic (Wu and Yao 2004). There are numerous lakes and swamps in the interior parts of the plain.
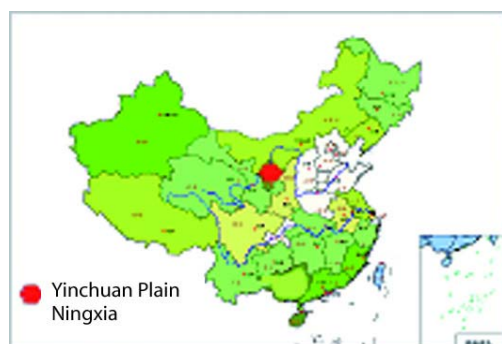
Figure 1. Location of the Yinchuan Plain in China

The climate of the Yinchuan Plain is arid, with a mean annual rainfall of approximately 200 mm, about 60–75% of which falls between July and September. Precipitation provides only about 10–20% of total crop water requirements. Average annual potential evaporation is around 1400 mm and there are 140–160 frost-free days. The average annual temperature is approximately 9°C.

Around 2.7 million people live on the plain, which has a history of more than 2000 years of agriculture and irrigation development. The first canal was constructed at the southern end of the Yinchuan Plain during 214 BC. Early in the Qing Dynasty (214 BC) up until the 1960s, more than 10 main canals and 13 main drains were constructed to meet the irrigation and drainage requirements of the plain (Figure 3). Total irrigation water withdrawal from the Yellow River is around 5600 GL/annum for 450,000 ha of irrigated area on the plain (Feng 2003). The agricultural sector consumes 93% and the remainder is used by industry and for domestic water supplies. The main crops are rice, wheat and maize, but fruits and vegetables are also grown. Raising fish in the lakes and ponds is also common.
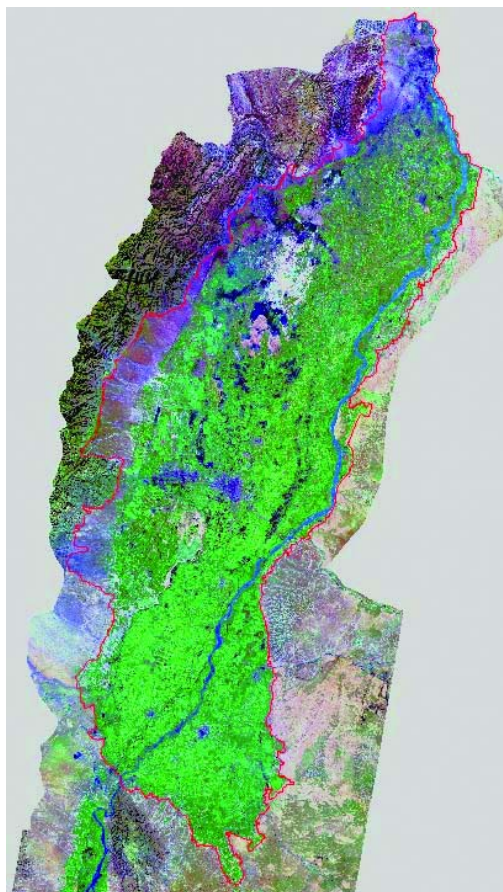
Figure 2. Map of the Yinchuan Plain, Ningxia Autonomous Region, northwestern China

Irrigation occurs mainly through flood and furrow irrigation. The efficiency of the irrigation system is, as a whole, very low (36%). Application rates of 15 ML/ha (1000 m^3/mu) to 24 ML/ha (1600 m^3/mu) are reported for crops where a crop evapotranspiration demand of 7.5–9.0 ML/ha (500–600 m^3/mu) is expected. Rice irrigation is reported to be up to 49.5 ML/ha (3300 m^3/mu); that is, 2–3 times the actual crop need. The cause of this poor performance is complex but includes inadequate and poor management of water distribution systems to farms and on farms, inefficient irrigation practices and low water

prices, the last discouraging investment in higher value crops, more efficient production methods or groundwater pumping (Wang and Gan 2003). Excessive use of irrigation water over time, poor subsurface drainage and excessive seepage from poorly maintained irrigation and drainage systems has resulted in increased accessions to groundwater, causing the watertable to rise at an alarming rate on some parts of the plain (0.2 m/year). As a result, shallow watertables (1–2 m) have developed in most of the northern parts of the plain. This has led to the development of secondary salinity in about 40% of the plain (Anyin 2002). In some areas, the problem of salinisation has become very severe. Excess water from irrigation water overuse has been discharged into the drainage system. This drainage water exports nutrients, causing pollution of surface water resources of the plain. The drainage system of the plain also receives rural sewage and effluent from local industries.

Drainage water carrying excessive levels of nutrients and industrial and sewage contaminants is discharged into the Yellow River, polluting it and creating potential problems for the downstream users. The inland-irrigated areas of northern China are currently suffering from acute problems of (a) water shortage for irrigation and domestic water supplies, (b) rapid expansion of waterlogged areas, (c) degradation of soils due to alkalinity, sodicity and salinity, (d) increase in the rate of salt discharge to rivers and lakes, (e) depletion and contamination of groundwater and (f) increasing rates of discharge of nutrient and other pollutants to surface-water systems.

Sustainable agricultural production in the Yinchuan Plain requires urgent improvement in water and salinity management; otherwise the agriculture sector is likely to face serious water availability, water quality, land degradation and environmental pollution problems. The overall aim of the research reported on here was to improve water and salinity management on the Yinchuan Plain to increase grain production and the availability of good quality water for agricultural and other uses, reduce soil salinisation and minimise environmental pollution.
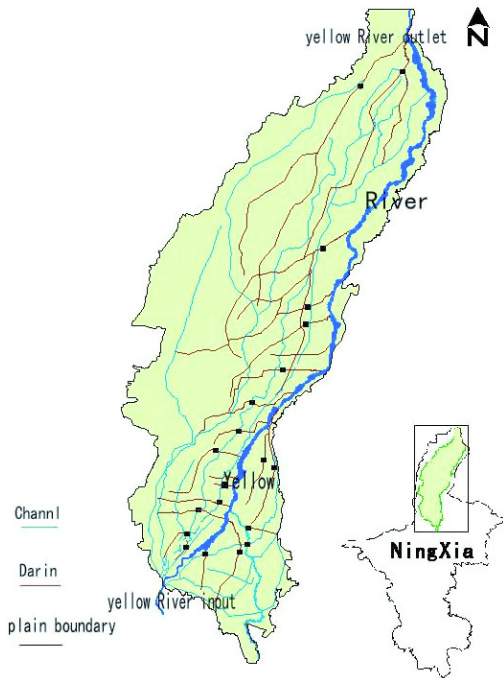

Figure 3. Map showing the Yellow River and the irrigation and drainage network on the Yinchuan Plain
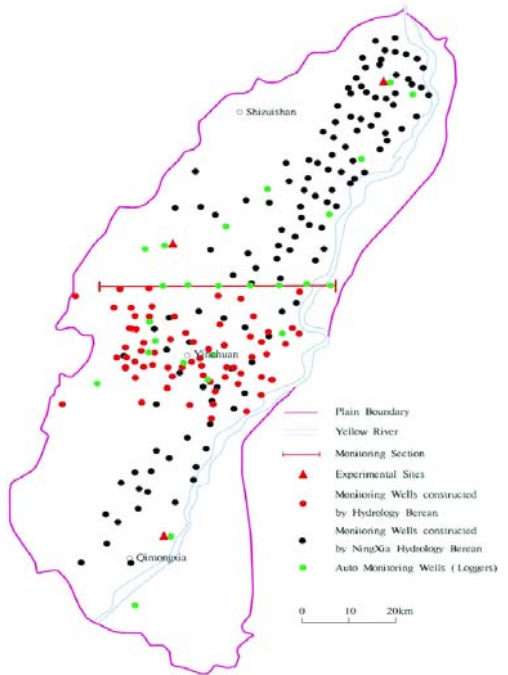

Figure 4. Locations of the network of observation wells on the Yinchuan Plain

Material and methods

To improve water and salinity management on the Yinchuan Plain it was first necessary to evaluate the water resources of the region, identify mechanisms of water wastage, quantify the main processes causing soil salinisation and development of shallow water-tables, trace sources of surface water pollution, and then suggest strategies for their improvement.

To determine hydrological response units (HRU) of the Yinchuan Plain, groundwater level data for the past 20 years were collected, collated and analysed. The regional geology, landform characteristics, lithology and aquifer structure were also collected and collated. The HRU were constructed with the help of time series of groundwater level data and other hydrological and physical properties of the plain and aquifers, following the procedure described by Salama et al. (2002). The plain has an extensive network of new and existing observation wells (Figure 4). The groundwater data from these wells were analysed for the past 20 years to assess the rates of water level rise (RR) and depth to water table (DTW) in various parts of the Yinchuan Plain. A weighting factor (HZ) was introduced for any differences in the regional geographic position, landform unit, lithology of stratum and aquifer structure. Accordingly, the Yinchuan Plain can be divided into eight hydrological units (Figure 5) and a weighting factor for each unit is given in Table 1. Zhang et al. (2004b) give further details of the methodology. The HRU was calculated as:

$$HRU = DTW \times RR \times HZ \qquad (1)$$

Over 300 groundwater and 200 soil samples were collected during 2002 and 2003 to assess and map groundwater and soil salinity on the Yinchuan Plain. These data were also required for geochemical modelling and analyses. Remote sensing was used to assess the soil salinity, with soil sampling data used for ground-truthing.

Water pollution is a major issue on the Yinchuan Plain where contaminants from farms, rural sewage and industrial waste is polluting the surface water resources of the plain and the Yellow River. To quantify the rates of flow and pollutant discharge into drains, canals and the Yellow River, and assess the sources and types of pollutant discharge, Huinong canal and associated drains were selected for study. Huinong canal is one of five main major canals on Yinchuan Plain. Drain No. 5 associated with this canal discharges into the canal 10 km upstream of its outlet into the Yellow River. Electrical conductivity (EC) loggers were installed at various locations in the canal, drain and Yellow River to monitor water

Table 1. Hydrogeological conditions and weighting factors for hydrological zones in the Yinchuan Plain

ID	Name of zone	Lithology of aquifer	Depth (m)	Aquifer yield (m^3/day)	Total dissolved solids (g/L)	Depth to watertable (m)	Weighting factor
a	Qintongxia pluvial fan	Sand and gravel	10–300	2000–5000	<1	0.5–4	3
b	Pluvial gradient plain of Helan mountain foot	Gravel	>100	1000–5000	<1	5–30	3
c	Wu-Lin plain east Yellow River	Sand and fine sand	10–50	500–2000	<3	1–5	6
d	Alluvial plain of south Yinchuan Plain	Mid-sand and fine sand	10–40	500–2000	<1	1–10	5
e	Alluvial plain of Yinchuan		10–40	500–2000	<1	1–5	5
f	Fluvial and lacustrine plain of Yinchuan		10–50	500–2000	1–3	0.5–5	8
g	Fluvial and lacustrine plain of north Yinchuan Plain		20–50	500–2000	1–5	0–5	9
h	Taole plain zone		100	500–2000	<3	0.5–5	7

salinity, and ultrasonic doppler instruments (UDIs) to monitor flow. Water quality was monitored through regular sampling.
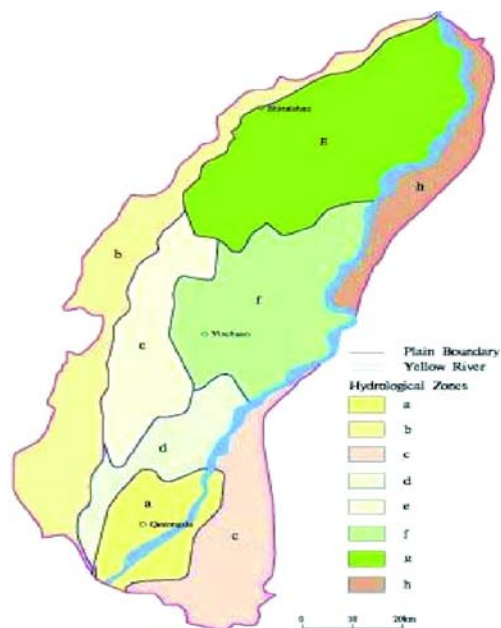

Figure 5. Hydrological zones of the Yinchuan Plain

Groundwater modelling was conducted to assess over-exploitation, if any, of the groundwater resource within the Yinchuan city area, determine the rates of groundwater abstraction that will be sustainable and identify optimal location of the well field to avoid pollution of deeper groundwater. All previous groundwater abstraction data and groundwater level data from various aquifers were collected and collated. These data were used to calibrate the groundwater model MODFLOW (McDonald and Harbaugh 1988). After its calibration, the model was used to simulate various management scenarios as detailed in Zhang et al. (2004a).

To assess the feasibility of conjunctive water use and use of shallow groundwater, a site was selected in the Huinong District of Shizuishan, Ningxia, where field experiments were conducted by using (1) Yellow River water; (2) Yellow River water and pumped groundwater alternately; (3) shallow groundwater; and (4) a 50:50 mixture of the two. A randomised block design was adopted and there were three replications for every treatment. Each plot had an area of 129.6 m^2 (3.6 × 36 m). Crops grown were

spring wheat and maize planted as mixed cropping. The spring wheat was seeded on 7 March 2004 and harvested on 15 July 2004. The maize was seeded on 10 April 2004 and harvested on 1 October 2004. Five irrigations were applied during the growing season. Approximately 90 mm depth of water was applied in each irrigation. In April and October, soil samples were collected from various depths of the soil profile above the watertable for soil moisture, soil chemistry and salinity analysis. Groundwater samples were also collected to assess any changes in the quality of groundwater as a result of irrigation with varying quality water. Crop yields were measured from each plot and crop.

To assess water-use efficiency of furrow and flood irrigation methods, a site was selected in the Huinong District of Shizishan, Ningxia, and field experiments were conducted to assess any water savings from using furrow irrigation rather than the traditional flood irrigation for growing Chinese wolfberry and evaluate impacts, if any, on crop yields and salinity build-up in the soil profile. An extensive area within the Yinchuan Plain is planted with Chinese wolfberry. The field experiments were conducted during 2003. There were two treatments (flood and furrow) with one replication for each treatment. Both treatments were planted with Chinese wolfberry. Each of the two plots in the flood irrigation treatment had an area of about 700 m^2 (36.6 × 19.1 m), whereas each of the two plots in the furrow irrigation had an area of 620 m^2 (35.5 × 17.5 m). The soil moisture from various segments of the soil profile up to 1.2 m depth was measured regularly during the growing season. Both treatments were irrigated on the same day but irrigation depths varied between two treatments.

The Junmachang and Jinshan sites, affected by both salinity and waterlogging, were selected to examine the changes in soil salinity adjacent to a drainage system, patterns of groundwater seepage into the drain and monitor changes in the soil and water chemistry. The sites were instrumented with transects of shallow piezometers for the continuous monitoring of groundwater levels adjacent to the drainage system and EC meters to monitor drain water quality. Soil was sampled twice a year at two locations along each transect of piezometers and analysed for major ions and pH.

Sand Lake and surrounding brackish areas were selected to study groundwater discharge patterns and their effect on the development of surrounding brackish areas and to identify management options

that will help minimise adverse impacts to these areas. Sand Lake is one of the most important tourist sites in the Ningxia Autonomous Region. Due to the continuously rising water levels and the increasing salinity of the unconfined aquifer, groundwater discharge to the lake is increasing. A brackish area north of the lake is another groundwater discharge zone. Although there are about 50 monitoring wells covering a 50 km radius, there is not enough information to reliably identify the aquifers that are discharging into the brackish area. Transects of both deep and shallow piezometers were installed to assess the rates of recharge and discharge between various aquifers, and groundwater discharge to the soil surface. Electrical conductivity meters were installed to monitor the lake water salinity. Soil sampling of the surrounding brackish area was conducted regularly to monitor changes in the soil chemical composition. A weather station was installed to monitor weather parameters, and a database was established for the study area. All previously collected data were collated and stored in the database. Groundwater modelling was conducted to assess the impacts of various water levels in the lake on the rates of groundwater discharge to the surrounding areas.

Results and discussion

Hydrological response units (HRU) of the Yinchuan Plain

The regional HRU were determined based on the weighing factors in various zones, rates of water level rise and DTW. The HRU for 1992 and 2000 are shown in Figure 6. The higher the HRU value, the bigger is the risk of developing a shallow watertable. Accordingly, the zones of shallow groundwater risk were located in the north of the Yinchuan Plain during 1992 and 2000. These areas need urgent attention to arrest the development of shallow water levels and risk of soil salinisation. Zhang et al. (2004b) provide further details about the HRU.

Water resource pollution

Total water resources available in the Yinchuan Plain are 42.33×10^8 m^3/annum, with a surface water resource component of 25.40×10^8 m^3/annum and a groundwater component of 16.93×10^8 m^3/annum (Zhao 1999; Zhang and Wang 2003). However, the quality of the Yellow River water deteriorates on the
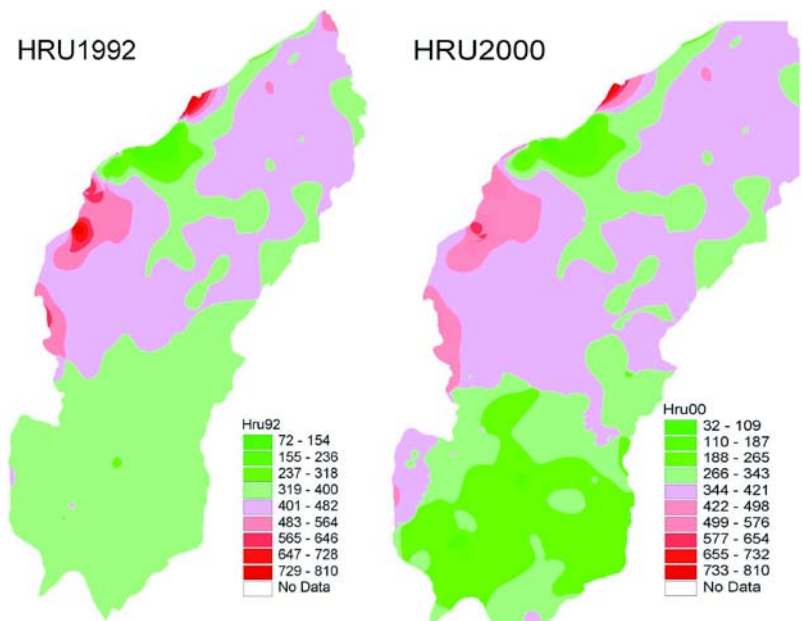

Figure 6. Hydrological response units (HRUs) of the Yinchuan Plain in 1992 and 2000

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Yinchuan Plain due to the discharge of drainage water containing excessive salts, nutrients and other pollutants (Figure 7). Salt concentrations also increased: at the inlet of the plain (Qingtongxia) in 2002, the average concentration of total dissolved salts (TDS) of the Yellow River was 440 mg/L whereas at the outlet it was 555 mg/L.
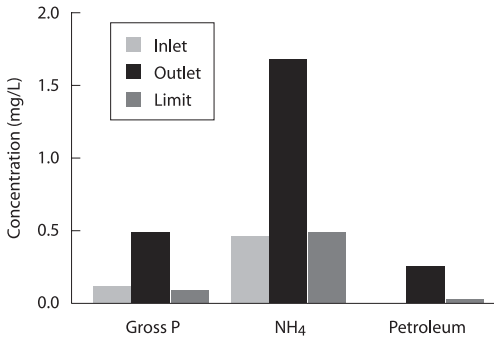
Figure 7. Yellow River water quality at the inlet and outlet of the Yinchuan Plain

The main drains discharged the most polluted water into the Yellow River. The pollutants included NH_4, phosphorus, chloride, sulfate, biological oxygen demand (BOD) and volatile hydroxybenzene. The TDS at the outlets of main drains was in the range 750–1740 mg/L. Water quality in the Sand Lake and West Lake also deteriorated over time. The shallow groundwater in more than 50% of the Yinchuan Plain has been polluted to some extent. Over 40% of the water samples from first confined aquifer also contained NH_4 at concentrations between 0.01 and 1.95 mg/L.

Over-exploitation of groundwater

Groundwater modelling showed that there was over-exploitation of groundwater resources in urban Yinchuan city. Over-exploitation from confined aquifers has caused excessive drawdown in the confined aquifers, resulting in downward pressure gradients and leakage of polluted water from shallow aquifers. The local government plans to increase groundwater abstraction to 2355×10^8 m^3/annum during the next five years (Zhu and Xia 2002). Pumping these volumes from confined aquifers will cause excessive drawdown in the second and third confined aquifers (Table 2). To control the rate of water level decline, and therefore pollution in the second and third aquifers, the location of some of the water fields should be changed and pumping yields from the third aquifer should be reduced. The modelling scenarios and results are explained in Zhang et al. (2004a).

Soil and groundwater salinity

According to analyses of the soil sampling data, the main soil types in the Yinchuan Plain include alkaline and calcareous silt and clay loam soils. The average soil pH is around 8.2. The main primary minerals are hydromica, chlorite, kaolinite and smectite. The secondary minerals are calcite, gypsum, dolomite and halite. The salt content of the soil tends to decrease with depth from soil surface to the groundwater level. There was a medium salinity hazard in extensive areas of the Yinchuan Plain. The areas of high salinity hazard were relatively small.

The groundwater had an average pH of about 8. The TDS of most of the groundwater ranged between 1 and 3 g/L (Figure 8). The areas of either less than 1 g/L or greater than 3 g/L TDS groundwater were relatively small. The chemical characteristics of shallow groundwater were similar to that of soil, indicating geochemical interactions between soil and shallow groundwater.

Table 2. Impact of pumping on groundwater levels in the Yinchuan city area

	Aquifer ID	2000	2005	2010
Pumping (10^4 m^3/day)	II	14.1	14.1	24
	III	6.2	6.2	21
Area of cone of depression (km^2)	II	350	1020	1023
	III	248	700	992
Depth to water in the cone centre (m)	II	25.4	25	33
	III	17.2	14	40
Annual mean decline rate (m)	II		0.31	1.24
	III		0.39	2.32

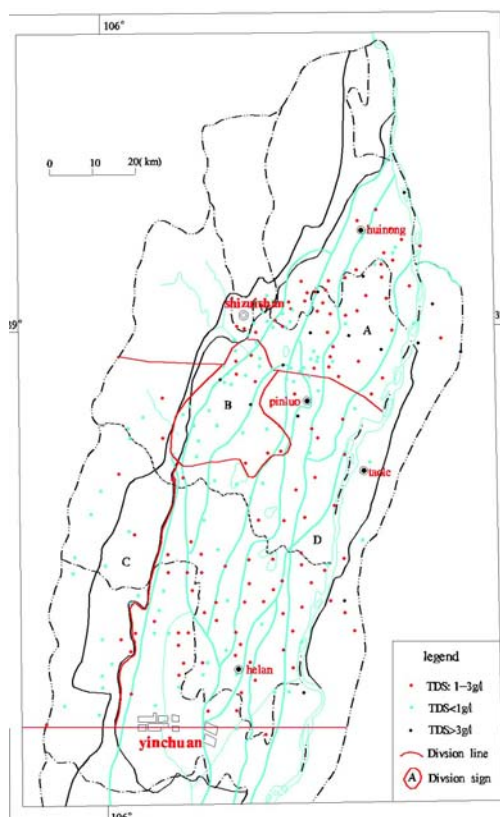**Figure 8.** Zones (A, B, C and D) of distinct groundwater quality in the Yinchuan Plain

Conjunctive water use

Groundwater quality data were also used in the geochemical modelling to assess the feasibility of mixing it with surface water and using it for irrigation. The plain was divided into four zones (A, B, C, D) depending upon the groundwater quality (Figure 9). The PHRREQC (Parkhurst 1995) model was used for this purpose. This model has been used for a similar study in the Ord River Irrigation Area (ORIA), northern Australia (Ali et al. 2002). The chemical composition of Yellow River water was used for canal water (CW, 498 mg/L). Representative groundwater qualities in the zones A, B, C and D were from wells W13 (2365 mg/L), W89 (1135 mg/L), W46 (955 mg/L) and W43 (1270 mg/L) respectively. The Yellow River water was mixed with the groundwater from these zones in various proportions (80:20 to 50:50) in the PHREEQC model and suitability for irrigation of the resultant

water quality (salinity and sodicity risks) assessed. The modelling results showed that there will be high risk of salinity development if these mixtures are used for irrigation over long periods without providing adequate and regular leaching. Both salinity and sodicity risks will be higher in zone A of the Yinchaun Plain (Figure 9). In this zone it will be feasible to mix up to only 20% groundwater with the surface water to irrigate relatively salt-tolerant crops only. In other zones it will be safer to mix 20% groundwater with surface water for irrigation of crops. However, salt-sensitive crops will be affected by this water. Only in zones B, C and D will it be feasible to irrigate salt-tolerant crops if 50% groundwater is mixed with surface water. Heavy irrigation applications at regular intervals will be required to avoid salinity build-up in the soil profile. The use of this resource for irrigation will reduce pressures on the Yellow River water and help lower watertables on the Yinchuan Plain. Further details on geochemical modelling and results are given in Shi (2004).

Taking crop yields obtained by using the Yellow River water as a benchmark, there was significant reduction in the crop yields when pumped groundwater alone was used for irrigation (Table 3). There were no significant differences in the crop yields when either alternate irrigation with Yellow River water and pumped groundwater, or a mixture of Yellow River water and groundwater was applied. The results show that it is feasible to mix shallow groundwater with surface water up to 50% without any significant reductions in the crop yields. Salt accumulation will be expected over time which can be avoided using regular leaching applications. Using the pumped groundwater alone would not be feasible and would result in crop yield reductions along with salt accumulation in the soil profile.

Table 3. The impact of use of irrigation water of varying quality on average crop yields

Treatments	Mean yield of wheat and maize (t/ha)
Irrigation with Yellow River water	19.0
Mixture (50:50) of pumped water and Yellow River water	18.9
Irrigation with, alternately, pumped water and Yellow River water	17.9
Irrigation with pumped water	15.4
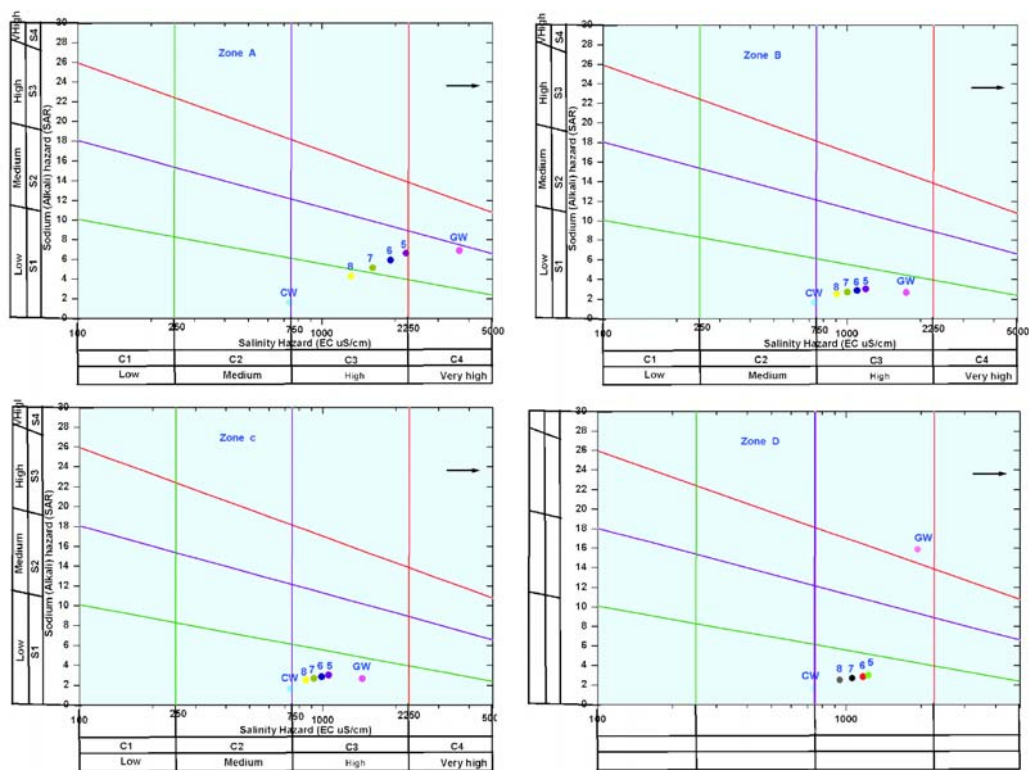
Figure 9. Potential salinity and sodicity risks of the use of various mixtures of surface and groundwater for irrigation (GW: groundwater; CW: canal water; 8: 80% surface water and 20% groundwater)

Irrigation techniques

The averages of pH and EC of the top 1.2 m of loamy soil in the experimental plots were 8.3 and 80 mS/m, respectively. The soil moisture variation during the growing season in the two treatments is shown in Figure 10. The average water content was similar in both furrow and flood treatments during initial stages of crop growth. It was lower for furrow irrigation during later stages of the crop growth. However, it always remained above 50% of field capacity throughout the monitoring period for both treatments.

The irrigation amounts were the same for the first two irrigations but significantly less for furrow irrigation treatment afterwards (Table 4). Total water applied in the furrow irrigation treatment was 35% less than that for flood irrigation but the average yields of wolfberries were similar for both treatments (13.3 and 13.1 t/ha, respectively). Therefore, a significant amount of water can be saved if the furrow irrigation technique is used instead of flood irrigation. The irrigation water

productivities for the flood and furrow irrigation treatments were 2.2 and 3.4 kg/m^3, respectively. For the furrow irrigation method, salt would be expected to accumulate in the soil profile over time. This could be avoided by applying regular leaching applications.
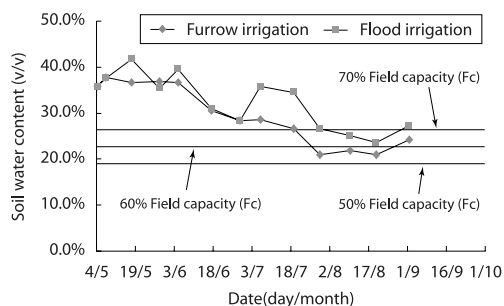
Figure 10. The dynamics of soil water content following use of one or other of two irrigation techniques

Table 4. Irrigation amounts applied in flood or furrow irrigation

Treatment	Water applied (mm)						
	15/11/02	19/04/03	11/05/03	11/06/03	28/06/03	11/09/03	Total
Flood irrigation	135	105	105	102	67	84	598
Furrow irrigation	135	105	33	42	39	29	383

Seepage from channels and drainage effectiveness

Several sites were selected and instrumented to monitor the rates of seepage from various irrigation channels to surrounding agricultural land. Analyses of the collected data suggested that there was excessive seepage from the channel network. This seepage results in wastage of water and also causes rising groundwater levels. Higher groundwater levels near irrigation channels, and groundwater gradients sloping away from channels, suggest that there is continuous seepage from channels. The main causes of seepage include poor maintenance, higher hydraulic heads (water levels in the canals are higher than ground surface levels to serve the command area) and insufficient protection from farm animals and machinery.

The effectiveness of deep, open drains was evaluated at two sites by installing transects of both shallow and deep piezometers. The groundwater levels in these piezometers were monitored from 2001 to 2004. Analyses of the monitoring data suggested that the drains were effective in lowering the groundwater levels surrounding deep open drains. Their areal influence was between 100 and 150 m at two sites. Soil root-zone salinity at various depths up to watertable level was also monitored. It took two years for the soil salinity to improve to levels suitable for crop growth. The crops were grown three years after drain construction at both sites. The biomass productivity at both sites was comparable to that at adjacent sites unaffected by soil salinity and waterlogging.

Surface and groundwater interactions in the Sand Lake and surrounding brackish areas

The monitoring of groundwater levels surrounding the Sand Lake site, and surface water levels in Sand Lake, suggested that the water levels in the lake are usually very high during the rainy season. This results in groundwater recharge, causing the groundwater levels to rise in the surrounding areas and development of additional brackish areas. Ground-water levels gradually fall away from the Sand Lake, suggesting groundwater recharge. During the dry season, the water levels in Sand Lake are generally lower, and surface water from canal and drainage system is usually pumped into the lake to maintain the water levels required. The groundwater modelling suggested lowering the currently maintained water levels in the Sand Lake by 0.5 m to reduce groundwater recharge and therefore the development of additional brackish areas. Groundwater modelling also showed that the higher, shallow groundwater heads surrounding the lake have resulted in the development of downward pressure gradients. This is causing leakage of low-quality shallow groundwater into the first confined aquifer leading to its pollution. The groundwater samples from the first confined aquifer showed higher levels of NH_4 and other pollutants, supporting the modelling results.

Conclusions

The hydrological response units for the Yinchuan Plain identified high-risk areas that need urgent attention to arrest the development of shallow water-table levels and soil salinisation. The quality of the shallow groundwater is low, and there is a medium soil salinisation risk in extensive areas of the Yinchuan Plain. The geochemical modelling suggested strong interactions between surface water, soil and shallow groundwater. On most of the Yinchuan Plain it is feasible to mix 20% shallow groundwater with surface water for irrigation, provided adequate leaching applications are applied regularly. In some parts of the Yinchaun Plain it is feasible to mix up to 50% shallow groundwater with surface water for irrigation of crops that are relatively salt tolerant.

There is widespread pollution of both surface and groundwater resources of the Yinchuan Plain. The pollution of surface water resources occurs from nutrients and industrial waste, along with excessive discharge of salts into the Yellow River. The surface water quality in the major lakes has also deteriorated over time. The shallow groundwater in more than

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50% of the area of the Yinchuan Plain has been polluted, and over 40% of the water samples from the first confined aquifer contain NH_4 above acceptable limits. In some areas of the Yinchaun Plain over-exploitation from the first and second confined aquifers is causing leakage of polluted shallow groundwater into the first confined aquifer.

A reduction in crop productivity is expected if shallow groundwater alone is used for irrigation. No significant differences in the crop productivity are expected if either alternate irrigation of the Yellow River water and pumped groundwater, or a mixture of Yellow River water and groundwater, is applied as irrigation. It was shown through field experiments that a significant quantity (35%) of water can be saved if furrow irrigation is used instead of flood irrigation, with no significant impacts on yield.

Field experiments on the rates of seepage from irrigation channels suggested excessive seepage from these channels, resulting in the development of shallow watertables and soil salinity. From the results of trials on the effectiveness of deep, open drains, it was concluded that these drains are effective in lowering the water levels and reducing soil root-zone salinity. Their areal effectiveness ranges from 100 to 150 m. Groundwater modelling showed that, to reduce groundwater recharge and avoid the development of additional brackish areas surrounding Sand Lake, it is necessary to lower the water levels in the Sand Lake by 0.5 m.

The impacts of this research are significant. Farmers and state agencies now treat irrigation and drainage management as one of the most serious issues. Based on these research findings a new plan is being prepared to control salinity and improve crop yield. There is already an increased investment by the government in the irrigation and drainage sector. Following reduction in irrigation water withdrawal from the Yellow River, about 3000 shallow groundwater wells have been constructed to supplement irrigation, lower shallow watertables and reduce the risk of salinisation. A process for establishing associations of farmers who use irrigation water has been initiated for the purposes of encouraging them to apply water-saving techniques to reduce water wastage, introduce gradual irrigation water price increase, educate farmers about the optimal use of fertilisers and pesticides, and increase their awareness of the sources of water resource pollution and potential risks.

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Effects of groundwater depth and water-saving irrigation on rice yield and water balance in the Liuyuankou Irrigation System, Henan, China

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Abstract

Declining water availability has led to the development of water-saving technologies for rice, such as alternate wetting and drying (AWD) and aerobic rice (high-yielding rice grown in nonflooded soil). Little is known about the performance of these systems under different hydrological conditions, and their impacts on the water balance of rice fields. This study quantified the effects of groundwater depth (GWD) and irrigation management on yield, water productivity, and water balance for lowland and aerobic rice in the Liuyuankou Irrigation System (LIS) in Henan, China, using a modelling approach. We parameterised and evaluated the crop model ORYZA2000 using 4 years of field experiments. ORYZA2000 was sufficiently accurate in simulating the observed crop and soil water variables. We ran ORYZA2000 with 24 years of historical weather data for different groundwater depths and water management options: continuous flooding (CF); AWD with re-irrigation at 5 and 10 days after the disappearance of ponded water; aerobic with re-irrigation when soil water potentials in the root zone dropped below –10, –15, –20, –30, and –50 kPa; and rainfed. In lowland rice, AWD gave yields similar to those of CF but saved 30–60% of irrigation water by reducing percolation flows by 50–80%, and had little effect on evaporation and transpiration. AWD irrigation management increased total water productivity (WP) by 30–60%. Shallower groundwater depth had a significantly higher grain yield than deeper groundwater depth in lowland rice production. In aerobic rice, yield declined by 10%, going from a –10 to –50 kPa irrigation threshold level, but irrigation inputs decreased by 80% because of an equivalent reduction in percolation. WP increased 60% when the threshold soil water potentials decreased from –10 to –50 kPa. Average yield at lower groundwater depth (20–120 cm) was 39% higher than at deeper groundwater depth (1000 cm). The results indicate that AWD and aerobic rice maintain high yields and save irrigation water with shallow GWD in the area.

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河南柳园口灌区地下水位和节水灌溉对水稻产量及

水分平衡的影响研究

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摘要 应对水资源的减少，出现了不少水稻节水技术，如干湿交替灌溉（AWD）和旱稻种植。然而，这些方式在不同的水文条件下的表现以及对稻田水分平衡的影响还了解甚少。本文采用模型方法，定量研究了河南柳园口灌区（LIS）地下水位和灌溉管理对水稻与旱稻产量、水分生产率及水分平衡的影响。利用 4 年的大田数据对水稻模型 ORYZA2000 进行了参数化和验证，表明 ORYZA2000 可以对观察的作物与水分变量进行精确的模拟。采用 24 年的历史天气数据，在不同地下水位和水分管理组合下运行 ORYZA2000 模型，不同水分管理包括：连续漫灌（CF）；在积水层消失 5 天和 10 天后的干湿交替（AWD）灌溉；当根区土水势降到-10，-15，-20，-30和-50 kPa 时进行灌溉的旱稻种植，以及雨养条件种植（RF）。对于低地水稻，AWD 处理的产量接近于 CF 处理，但由于渗漏减少达 50-80%，AWD 处理可节约灌溉水 30-60%，且 AWD 处理的蒸发和蒸腾影响较小。AWD 灌溉方式可增加水分生产率（WP）达 30-60%。浅地下水位的水稻产量显著地高于深层地下水位的产量。对于旱稻，从灌溉指标-10 到-50 kPa，产量减少 10%，但是由于渗漏的减少灌溉量减少达 80%。当灌溉指标从-10 到-50 kPa，水分生产率增加 60%。较低地下水位（20 到120cm）的平均产量比深层地下水位（1000cm）高出 39%。上述结果表明，柳园口灌区（LIS）浅层地下水位条件下干湿交替灌溉（AWD）和旱稻种植可保持较高产量同时能达到节水的目的。

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Introduction

The lower Yellow River Basin is one of the most important food production areas in China. The Liuyuankou Irrigation System (LIS), one of the typical irrigation systems in this region, is located in eastern Kaifeng City, south of the Yellow River, and encompasses an area of about 40,700 ha.

With the declining water availability in irrigation systems, water-saving technologies at the field scale are being developed to reduce the rice water requirement. These technologies include alternate wetting and drying (AWD), flush irrigation (FI), and aerobic rice. In AWD, the rice field is allowed to dry for a few days between irrigation events, including a mid-season drainage in which the field is allowed to dry for 7–15 days at the end of the tillering stage. The AWD system has been reported to save water and to maintain or even increase yield, and to be widely adopted by farmers (Li 2001). Belder et al. (2004) compared the effects of AWD and continuous flooding (CF) irrigations on rice performance and water use at different levels of nitrogen (N) input in typical lowland environments and concluded that biomass and yield did not differ significantly between AWD and CF, but AWD could reduce water

Abbreviations used	
AWD	alternate wetting and drying
C	capillary rise
CF	continuous flooding
CV	coefficient of variation
D	deep drainage
DAE	days after emergence
DAT	days after transplanting
E	evaporation
FI	flush irrigation
GWD	groundwater depth; depth of the top of the watertable
I	irrigation
LAI	leaf area index
LIS	Liuyuankou Irrigation System
P	percolation
PRF	partially rainfed with survival irrigation
R	rainfall
RF	rainfed
SD	standard deviation
T	transpiration
WMO(s)	water management option(s)
WP	water productivity

use up to 15% without affecting yield when the shallow groundwater stayed within about 0–30 cm. A new development in water-saving technologies is the concept of 'aerobic' rice (Bouman et al. 2005). In the aerobic rice system, special high-yielding aerobic rice varieties are grown in unsaturated aerobic soils throughout the season, just like an upland crop such as wheat or maize, with supplementary irrigation and sufficient external inputs to reach high yields. The aerobic condition is maintained by using flush irrigation or sprinklers, so that ponding occurs for only short periods just after irrigation or rain. Aerobic rice is targeted at water-short irrigated lowlands where the availability of water is too low to grow rice under the AWD regime and at favourable uplands with access to supplementary irrigation. Research in China and the Philippines suggested that yields of aerobic rice of around 70% of that realised under CF can be obtained using about 50% of the water used in CF systems (Bouman et al. 2005; Yang et al. 2005).

The potential of water-saving technologies to reduce water inputs and their effect on yield and water productivity depend on soil type, groundwater table depth, and climate (Bouman and Tuong 2001). The adoption of water-saving technologies may affect environmental conditions, which may have repercussions on the performance of these water-saving technologies themselves. For example, AWD and aerobic rice will change percolation, which may affect regional hydrological conditions such as groundwater recharge and level. Little is known so far about the performance of these water-saving irrigation systems under different hydrological conditions, however, or of their impacts on the crop yield and water balance of rice fields. Most research on AWD and aerobic rice has been limited to individual field experiments, and it has been suggested that simulation models should be applied to synthesise experimental findings and extrapolate them to different environments and agro-ecological conditions (Bouman and Tuong 2001; Belder et al., 2005).

Since the mid-1990s, the International Rice Research Institute and Wageningen University and Research Centre have been developing the 'ORYZA' series of models to simulate the dynamics of rice growth and development in potential (Kropff et al. 1994), N-limited (Drenth et al. 1994), and water-limited (Wopereis et al. 1996) situations. Recently, these models were integrated and updated in the single model ORYZA2000 (Bouman et al. 2001a,b). The model worked well for lowland rice under irri-

gated and rainfed conditions at various levels of N fertilisation in Indonesia (Boling et al. 2006).

The objectives of this study reported here are (1) to evaluate the rice crop growth model ORYZA2000 for traditional inbred and aerobic rice varieties under different water conditions in the LIS, and (2) to use ORYZA2000 to quantify the effects of different groundwater table depths (GWD) and irrigation management on grain yield, water balance components, and water productivity for lowland and aerobic rice conditions in the LIS. The implications of the findings for water management of the LIS are discussed.

Materials and methods

Field experiments

The field experiments were conducted at Kaifeng, Henan Province, China, in the summer seasons of 2001–2004. The site of the experiment in 2001 was a lowland rice-growing environment, Gaozhai village (34˚82'N, 114˚51'E, altitude 69.17 m). In 2002–2004, the experiments were in Panlou village (34˚78'N, 114˚52'E, altitude 68.05 m). The change in locations permitted the evaluation of the model in different hydrological conditions and the testing of the aerobic rice system.

The experiments were conducted in a split-plot design, with three replicates in 2001 and four in 2002 and 2004. In 2001 and 2002, the inbred rice variety XD90247 was used. In 2003 and 2004, aerobic rice variety HD297 was used. In 2001, the main plots were water treatments: (1) CF in puddled soil, (2) AWD in puddled soil, and (3) FI at –50 kPa soil water potential threshold level. In FI, there was no standing water in the field for most of the time. In 2002, the water treatments were three FI treatments with soil water potential threshold levels at –10, –30, and –70 kPa. A fourth treatment of 'partially rainfed with survival irrigation' (PRF) was included, in which irrigation was applied only when the rice crop showed very severe drought symptoms. In 2003 and 2004, the main plots were two irrigation regimes: (1) FI at a threshold level of –30 kPa and (2) PRF. The subplots were two N rates: N1, 225 kg/ha in 5 splits, and N2, 300 kg/ha in 5 splits. The subplots were two row spacings: D1 – spacing between rows at 30 cm, and D2 – spacing between rows at 24 cm.

All experiments were kept as free as possible from weeds, pests, and diseases. We measured phenology (date of transplanting, panicle initiation, flowering,

maturity, harvest); leaf area index (LAI) and green leaf, stem, and panicle biomass, and total dry matter at 15 days after emergence (DAE) and at 30 days after transplanting (DAT), panicle initiation, flowering, and grain filling; and grain yield. We measured daily standing water depth, soil water potential using tensiometers, irrigation input, drainage water, daily percolation rate, groundwater depth, and soil physical and hydraulic properties in different soil layers. These soil characteristics were used to determine van Genuchten parameters (van Genuchten 1980; van Genuchten et al. 1991) for the soil-water balance submodel in ORYZA2000.

Daily meteorological parameters (rainfall, pan evaporation, hours of sunshine, maximum and minimum temperature, wind speed etc.) were collected from the meteorological station at the Huibei experiment station some 8 km away from the site in 2001 and at 1 km from the 2002, 2003, and 2004 site.

Rice model ORYZA2000

Model description

ORYZA2000 simulates the growth, development, and water balance of lowland rice in situations of potential production, water limitations, and nitrogen limitations. It is assumed that, in all these production situations, the crop is well-protected against diseases, pests, and weeds. Bouman and Van Laar (2005) have presented a summary description and evaluation of ORYZA2000 for potential and N-limited situations. For water-limited conditions, the model includes soil-water balance modules PADDY (Bouman et al. 2001a,b) and SAWAH (Ten Berge et al. 1995). PADDY is suitable for typical, poorly drained lowland rice soils. SAWAH can be used for both lowland rice soils and regular 'upland' soils. In PADDY, a puddled lowland rice soil is modelled as a layer of muddy topsoil on top of a 3–5 cm plough sole, which overlies a nonpuddled subsoil. With ponded water on the surface, vertical water flow is either a fixed percolation rate or it can be calculated dynamically from hydraulic conductivity characteristics from the plough sole and the nonpuddled subsoil. The conductivity characteristics are expressed by either van Genuchten parameters or by parameters of a power function. With no ponded water on the surface, incoming water is redistributed by calculating gain and loss terms for all layers. All water in excess of field capacity is drained from the layer, with a maximum rate equal to the saturated hydraulic conductivity of the layer. The water reten-

tion characteristics are model input data and can be supplied either as measured data or as van Genuchten parameters. In SAWAH, the general flow equation is solved numerically under given boundary conditions, using explicit and implicit solution schemes for unsaturated and saturated layers of the soil profile, respectively. The pressure head is defined as zero at all saturated–unsaturated interfaces, and this condition is used as an internal boundary condition to calculate flow through the soil layers. For each soil layer, the conductivity curve and the water retention curve have to be specified by the van Genuchten parameters.

Model evaluation

The performance of ORYZA2000 for XD90247 and HD297 under lowland and aerobic soil conditions was evaluated using all four years of experimental data. Since two years of experimental data were needed for each variety to arrive at a good parameterisation, we could not distinguish an independent 'validation' data set. Following Bouman and Van Laar (2005), we used a combination of graphical analysis and statistical measures. We graphically compared the simulated and measured above-ground biomass, leaf area index, ponded water depth, soil water potential, and grain yield. For the same variables, we computed the slope (α), intercept (β), and coefficient of determination (R^2) of the linear regression between simulated (Y) and measured (X) values. We also calculated the Student's t-test of means assuming unequal variance ($P(t)$), and the absolute ($ARMSE$) and normalised ($NRMSE$) root mean square errors between simulated and measured values:

$$ARMSE = (1/n\ \Sigma(Y_i - X_i)^2)^{0.5} \tag{1}$$
$$NRMSE = 100*(1/n\ \Sigma(Y_i - X_i)^2)^{0.5}/\Sigma X_i/n \tag{2}$$

where n is the number of observations.

A model reproduces experimental data best when α is close to 1, β close to 0, R^2 close to 1, and $P(t)$ larger than 0.01, $ARMSE$ is similar to the standard deviation of measured values, and $NRMSE$ is similar to the coefficient of variation of measured values.

Model scenarios

We took the calibrated crop parameters of aerobic variety HD297 and inbred variety XD90247, and the soil properties and parameters representing the experimental conditions. We ran the ORYZA2000 model with 24 years of historical daily weather data from 1981 to 2004. These data were from the mete-

orological station at the Huibei experiment station in the LIS.

For the lowland rice system, we used the PADDY model to explore the performance of inbred rice variety XD90247 and the water balance under 49 scenarios: the combinations of seven water management options (WMO) and seven GWD. The water management scenarios were CF_25 10mm (CF, re-irrigate 25 mm when ponded water is lower than 10 mm), CF_75 10mm (CF, re-irrigate 75 mm when ponded water is lower than 10 mm), AWD_50mm10d (AWD, re-irrigate 50 mm 10 days after disappearance of ponded water), AWD_50mm5d (AWD, re-irrigate 50 mm 5 days after disappearance of ponded water), AWD_75mm10d (AWD, re-irrigate 75 mm 10 days after disappearance of ponded water), AWD_75mm5d (AWD, re-irrigate 75 mm 5 days after disappearance of ponded water), and rainfed (RF): purely rainfed, no irrigation. Seven generic GWDs were 20, 60, 90, 120, 150, 190, and 1000 cm below the soil surface, continuous from day 1 to day 365.

For the aerobic rice system, aerobic rice variety HD297 and the SAWAH model were used for 42 combinations of six WMOs and seven GWDs. Six water management options were used: FI –10 kPa (FI, irrigate 50 mm when soil water potential at 15 cm depth is –10 kPa), FI –15 kPa (FI, irrigate 50 mm when soil water potential at 15 cm depth is –15 kPa), FI –20 kPa (FI, irrigate 50 mm when soil water potential at 15 cm depth is –20 kPa), FI –30 kPa (FI, irrigate 50 mm when soil water potential at 15 cm depth is –30 kPa), FI –50 kPa (FI, irrigate 50 mm when soil water potential at 15 cm depth is –50 kPa), and RF. Seven generic GWDs were used: 30, 60, 90, 120, 150, 190, and 1000 cm below the soil surface, continuous from day 1 to day 365.

Simulation outputs were seasonal sums of evaporation (E), transpiration (T), irrigation (I), rainfall (R), growth duration (DAE for direct-seeded crop, and DAT for transplanted crop), and yield of rough rice. The water balance components (expressed in mm of water) in the field were computed according to

$$I + R + C = E + T + D + dW$$

where R = rainfall, I = irrigation, C = capillary rise, T = transpiration, E = evaporation, D = deep drainage, and dW is the difference in soil water storage in the field. Total water use at the field scale is the sum of the terms on either the left or right side of the equals sign. We defined percolation (P) as $P = I + R – E – T$; P includes dW, capillary rise, and

deep drainage. If P was negative, this indicated that capillary water and water from the soil layer were used. If P was positive, this indicated that water was added to the groundwater table.

Calculations and statistical analysis

Water productivity

Water productivity (kg grain/m³ water) was calculated as grain yield per unit of irrigation water ($WP(I)$) and per unit of total water (irrigation + rainfall) ($WP(I + R)$) from transplanting to harvest for lowland rice or from emergence to harvest for aerobic rice.

Statistics

Analysis of variance (ANOVA) was performed on water balance components and yield to determine the effects of water management options and different groundwater depths, and their interactions, using the IRRISTAT software. Differences among treatment means were evaluated. The level of confidence (P_c) was set at 95% or 99% depending on the parameters.

Results

Evaluation of ORYAZ2000 model

Model evaluation for crop variables

Figure 1 presents typical graphics of comparisons between simulated and measured biomass of total above-ground dry matter, green leaves, stems, and panicles, and of LAI of treatment FI30 of XD90247 in 2002 and treatment W1N1D2 of HD297 in 2003. The dynamics of LAI were simulated quite well for XD90247. Generally, LAI was under-simulated in the early growing season but quite well simulated after the mid growing season for HD297. The dynamics for biomass of total above-ground dry matter, green leaves, stems, and panicles were simulated well, except that simulated values for stem biomass exceeded the measured values at maturity for XD90247. The dynamics for biomass of total above-ground dry matter, green leaves, stems, and panicles were simulated quite well for HD297.
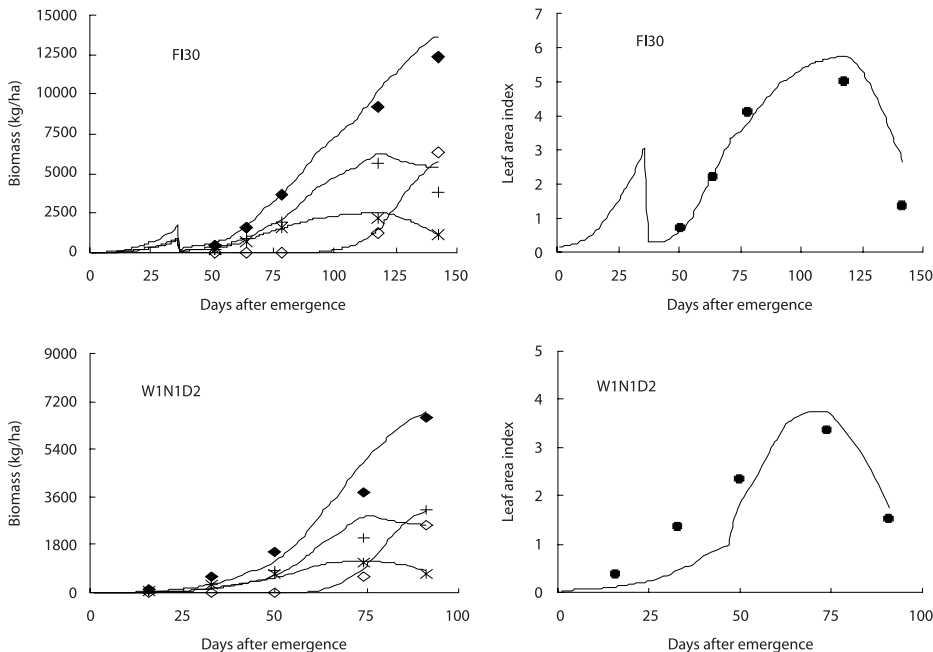

Figure 1. Simulated (lines) compared with measured biomass of total above-ground dry matter (◆), leaves (✳), stems (+), and panicles (◇), and of leaf area index (●) of typical treatments for XD90247 (above, FI30: flush irrigation (FI) at threshold level of –30 kPa) in 2002 and HD297 (below, W1N1D2: FI at threshold level of –30 kPa, 225 kg/ha N rate, 24 cm of row spacing) in 2003

Figure 2 compares simulated with measured grain yields for all the experiments. For reference, the 1:1 line plus and minus the SD of the measured variable is also shown. For XD90247, most of simulated yield data points fell within or very close to the 1:1 ± SD lines, indicating good simulation of yield. For HD297, the simulated yield data points fell within or near the 1:1 ± SD lines of measured ones. Generally, we see that the ORYZA2000 model provides a satisfactory simulation of grain yield for the inbred rice and aerobic rice varieties.
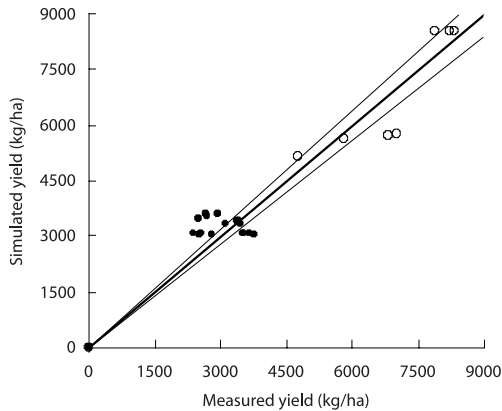
Figure 2. Simulated versus measured grain yield for XD90247 (filled circles) of 2001–02 and HD297 (open circles) of 2003–04 experimental data set. The thicker line is the 1:1 relationship; thinner lines are ±SD of the measured values around the 1:1 line

Table 1 gives the statistical parameters of goodness-of-fit for crop growth variables and grain yields of the whole experimental dataset. The means of sim-

ulated values were close to the measured ones. The biases (means of simulated values – means of measured values) of yield and final biomass were –121 and 1998 kg/ha for XD90247 and 199 and 405 kg/ha for HD297. The standard deviations (SD_p) of simulated values were also close to the measured ones. Student's t-test showed that the simulated and measured values of biomass of crop organs, LAI, and grain yield were all similar at the 99% confidence level. The linear relationship between simulated and measured values was highly significant, with R^2 values of 0.912–0.986 for XD90247 and 0.635–0.955 for HD297. The linear slope α was close to 1, except for LAI, with a value of 0.622, and yield, with a value of 0.751 for HD297. The intercept β approached 0 and the R^2 was close to 1, except for LAI, with a value of 0.752, and yield, with a value of 0.635 for HD297.

The values of ARMSE were 2201 kg/ha for total biomass and 660 kg/ha for yield of XD90247 and 740 kg/ha for total biomass and 560 kg/ha for yield of HD297. The values of NRMSE were 11–29%, with an average of 21% for XD90247, and 12–59%, with an average of 31% for HD297. The ARMSE values of crop growth variables and grain yield were 1.8 (1.5–2.2) times the SD in measurements for XD90247 and 2.1 (1.2–3.0) times SD in measurements for HD297. The NRMSE values of these crop variables were 2.1 (1.6–2.6) times the coefficients of variation (CV) in measurements for XD90247 and 2.2 (1.0–3.7) times the CV in measurements for HD297.

Model evaluation for soil water dynamics

Figure 3 presents typical graphics of comparisons between simulated and measured depth of ponded water in AWD and FI treatments for XD90247 in 2001.

Figure 3. Simulated (lines) and measured (symbols) depth of ponded water of alternate wetting and drying (AWD) and flush irrigation (FI) for XD90247 in 2001

Table 1. Evaluation results for ORYZA2000 simulations of crop growth variables over the growing season for the two varieties of the experiments from 2001 to 2004, Liuyuankou Irrigation System, China

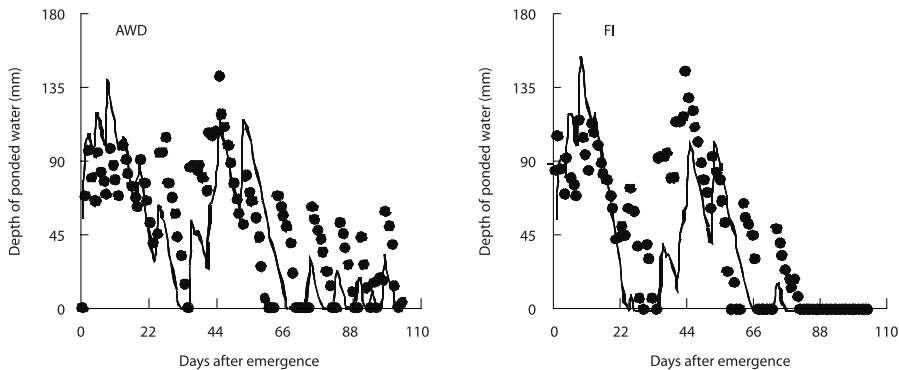| Crop variable	N	X_{mea} (SD_p)	X_{sim} (SD_p)	$P(t)$	α	β	R^2	ARMSE	NRMSE (%)	SD	CV (%)
XD90247 dataset (2001–02)											
Total biomass (kg/ha)	39	4998 (4971)	5382 (5490)	0.37**	1.075	8	0.95	1350	27	622	12
Biomass of panicles (kg/ha)	21	2597 (2865)	2591 (3046)	0.50**	1.049	–134	0.97	502	19	257	8
Leaf area index	39	2.33 (1.94)	2.63 (2.10)	0.26**	1.032	0.22	0.91	0.69	29	0.43	17
Final biomass (kg/ha)	8	10717 (4547)	12715 (5355)	0.22**	1.170	178	0.99	2201	21	1121	9
Yield (kg/ha)	8	6100 (2753)	5979 (2831)	0.47**	0.997	–102	0.94	660	11	439	7
HD297 dataset (2003–04)											
Total biomass (kg/ha)	96	2453 (2597)	2451 (2899)	0.50**	1.091	–225.5	0.955	653	27	365	14
Biomass of panicles (kg/ha)	48	1251 (1272)	1544 (1374)	0.14**	1.029	257.2	0.908	507	41	167	13
Leaf area index	96	1.91 (1.95)	1.42 (1.40)	0.02**	0.622	0.2	0.752	1.12	59	0.40	16
Final biomass (kg/ha)	17	6367 (1733)	6772 (1813)	0.26**	0.979	536.2	0.876	740	12	593	12
Yield (kg/ha)	17	2873 (869)	3072 (819)	0.25**	0.751	914.0	0.635	560	19	353	14

N = number of data pairs; X_{mea} = mean of observed values in whole population; X_{sim} = mean of simulated values in whole population; SD_p = standard deviation of population; $P(t)$ = significance of paired t-test, $P(t) > 0.01$ means that simulated and measured values are the same at the 99% confidence level; α = slope of linear relation between simulated and observed values; β = intercept of linear relation between simulated and observed values; R^2 = adjusted linear correlation coefficient between simulated and observed values; NRMSE (%) = normalised root mean square error (%); ARMSE = absolute root mean square error. SD = standard deviation of measured variables; CV = coefficient of variation of measured variables.

Table 2. Evaluation results for ORYZA2000 simulations of water dynamics of the whole experimental data set for XD90247 and HD297 from 2001 to 2004, Liuyuankou Irrigation System, China

Variable	N	X_{mea} (SD_p)	X_{sim} (SD_p)	$P(t)$	α	β	R^2	ARMSE	NRMSE (%)	SD	CV (%)
XD90247 data set (2001–02)											
Depth of ponded water (mm)	315	58 (37)	37 (52)	0.04**	0.833	4.07	0.511	32	55	23	60
Soil water tension (kPa)	338	9.236 (10.353)	10.353 (9.196)	0.48**	0.679	2.93	0.628	6.337	69	5.07	81
HD297 data set (2003–04)											
Soil water tension (kPa)	1320	12 (12)	14 (13)	0.00	0.48	8.159	0.222	13	107	3.81	52

N = number of data pairs; X_{mea} = mean of observed values in whole population; X_{sim} = mean of simulated values in whole population; SD_p = standard deviation of population; $P(t)$ = significance of paired t-test, $P(t) > 0.01$ means that simulated and measured values are the same at the 99% confidence level; α = slope of linear relation between simulated and observed values; β = intercept of linear relation between simulated and observed values; R^2 = adjusted linear correlation coefficient between simulated and observed values; NRMSE (%) = normalised root mean square error (%); ARMSE = absolute root mean square error. SD = standard deviation of measured variables; CV = coefficient of variation of measured variables.

Although the simulated values of ponded water depth exceeded the measured values in the early growing season and were below the measured values in the late growing season, the fluctuation of simulated field water depth agreed well with the dynamics of measured values.

Figure 4 presents typical graphics of comparisons between simulated and measured soil water potentials at 15 cm depth. The fluctuation of simulated soil water tension agreed well with the dynamics of measured values, although there was some spread in the measured data points. The dynamics of soil water tension were simulated well for the varieties by the ORYZA2000 model in the LIS.

Table 2 gives the statistical parameters of goodness-of-fit for ponded water depth and soil water tension of the whole dataset of XD90247 and HD297. As for crop variables, the means of the measured values were close to the simulated values. The bias (means of simulated values – means of measured values) of ponded

water depth was –21 mm for XD90247; the biases of soil water tension were –1.117 kPa for XD90247 and 2.00 kPa for HD297. The standard deviations (SD_p) of measured values were also close to the simulated values. Student's t-test showed that the simulated values of ponded water depth and soil water tension and the measured values were similar at $P_c = 99\%$ for XD90247. The linear relationship between simulated and measured values was highly significant, with R^2 values of ponded water depth of 0.511 for XD90247 and R^2 values of soil water tension of 0.629 for XD90247D502 and 0.222 for HD297 at $P_c = 99\%$. The slope α of the regression line was close to 1 and the intercept β was near 0 for XD90247.

The ARMSE value of ponded water depth was 32 mm. The NRMSE value was 55%. The ARMSE value was close to the SD in measurements and the NRMSE value of ponded water depth was similar to the coefficients of variation in measurements. The ARMSE values of soil water tension were 6.337 kPa for
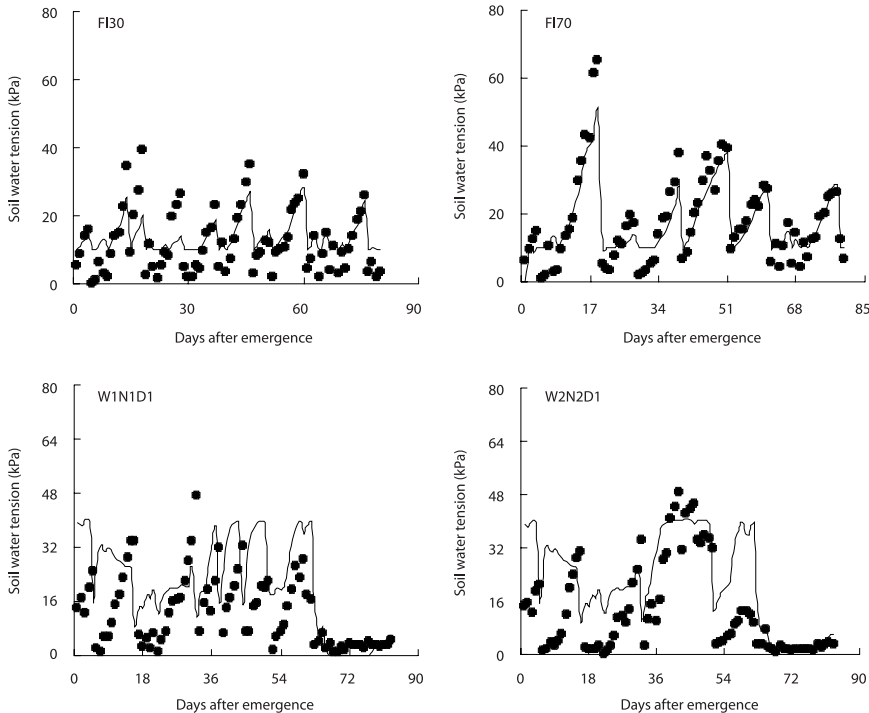

Figure 4. Simulated (lines) and measured (symbols) soil water potential at 15 cm depth of soil layer of typical treatments for XD90247 (above, FI30, FI70: FI at threshold level of –30 kPa, –70 kPa) in 2002 and HD297 (below, W1N1D1: FI at threshold level of –30 kPa, 225 kg/ha N rate, 30 cm of row spacing; W2N2D1: rainfed, 300 kg/ha N rate, 30 cm of row spacing) in 2003

XD90247 and 13 kPa for HD297. The NRMSE values were 69% for XD90247 and 107% for HD297. The ARMSE values were close to the SD in measurements for XD90247. The NRMSE values of soil water tension were close to the CV in measurements for XD90247 and twice the CV values in measurements for HD297.

Effects of water-saving irrigation and groundwater depths: lowland rice system

The ANOVA results showed that the major water balance components (percolation, transpiration, evaporation, and irrigation), grain yield, and water productivity were significantly affected by WMO, GWD, and their interactions at $P_c = 95\%$.

Effects of water-saving irrigation

Grain yield

Table 3 shows the means of grain yields under different WMOs. The mean yield ranged from 7188 kg/ha in RF to 7949 kg/ha in CF irrigation. The ANOVA results (Table 3) show that there were no significant differences between yields of AWD and CF irrigation, but that AWD and CF gave significantly higher grain yields than RF. This indicated that AWD is a water-saving practice, which has a yield similar to that of CF irrigation. From this scenario, the irrigation of AWD was 245–413 mm, while that of CF was 620–653 mm.

Table 3. Mean of yield and total water productivity (WP(I+R)) under different water management options (WMO)

WMO	Yield (kg/ha)	WP(I+R) (kg/m^3)
AWD_50mm10d	7915 a	1.35 a
AWD_50mm5d	7939 a	1.15 b
AWD_75mm10d	7925 a	1.22 b
AWD_75mm5d	7941 a	1.04 c
CF_25 10mm	7949 a	0.82 d
CF_75 10mm	7949 a	0.79 d
RF	7188 b	2.38 e

Note: statistical differences ($P \leq 0.05$) among numbers in the same column are indicated by different lower-case letters.

Water productivity

Table 3 shows total water productivity under different WMOs. WP(I+R) ranged from 0.79 kg/m^3 in CF with 75 mm re-irrigation to 2.38 kg/m^3 in rainfed. The ANOVA results (Table 3) showed that RF had a significantly higher WP(I+R) than both AWD and CF. AWD had a significantly higher WP(I+R) than

CF. AWD with re-irrigation of 50 mm 10 days after the disappearance of ponded water had a significantly higher WP(I+R) than other AWDs, whereas AWD with re-irrigation of 50 mm 5 days after the disappearance of ponded water and with re-irrigation of 75 mm 10 days after the disappearance of ponded water had a significantly higher WP(I+R) than AWD with re-irrigation of 75 mm 5 days after the disappearance of ponded water. There were no significant differences in WP(I+R) between the different CF irrigations. Water productivity fell with increasing irrigation. Although the water productivity of RF is much higher, the RF yield is much lower.

Water balance components

Figure 5 shows water balance components (and standard errors) under different WMOs. CF had a higher irrigation input, 620–653 mm, whereas AWD had a lower irrigation input, 245–413 mm. On average, AWD saved about half (49%) of the water. The largest irrigation input was for continuous flooding with re-irrigation of 75 mm when ponded water was lower than 10 mm. The smallest irrigation input was for AWD with re-irrigation of 50 mm 10 days after the disappearance of ponded water. Evaporation ranged from 81 mm in rainfed to 114 mm in continuous flooding irrigation. Transpiration ranged from 426 mm in rainfed to 440 mm in continuous flooding irrigation. Percolation ranged from 68 mm in AWD with re-irrigation of 50 mm 10 days after the disappearance of ponded water to 451 mm in continuous flooding with re-irrigation of 75 mm when ponded water is lower than 10 mm. CF had a percolation rate 70% higher than that of AWD. Percolation was negative, which indicated that the soil water supply (capillary rise) was used to satisfy evapotranspiration (ET). The trends of total water input under different water management options were the same as those of irrigation input.

Effects of groundwater depths

Grain yield

Table 4 shows the means of grain yields under different depths of the groundwater table (GWD). The mean yield ranged from 7573 kg/ha at GWD of 1000 cm to 7941 kg/ha at GWD of 20 cm. Yield decreased with increasing GWD. The ANOVA results (Table 4) showed that the yields at GWD of 20–190 cm were significantly different from the yield at GWD of 1000 cm at $P_c = 95\%$, but there were no significant differences between yields at GWD 20–150 cm and

60–190 cm. Shallower groundwater depth gave higher grain yields than deeper groundwater in lowland rice production.

Table 4. Mean of yield and total water productivity (WP(I+R)) under different groundwater depths

GWD (cm)	Yield (kg/ha)	WP(I+R) (kg/m³)
20	7941 a	1.35 a
60	7867 ab	1.26 ab
90	7867 ab	1.26 ab
120	7864 ab	1.26 ab
150	7857 ab	1.26 ab
190	7839 b	1.25 b
1000	7573 c	1.13 c

Note: statistical differences ($P \leq 0.05$) among numbers in the same column are indicated by different lower-case letters.

Water productivity

Table 4 shows total water productivity under different GWDs. WP(I+R) ranged from 1.13 kg/m³ at GWD 1000 cm to 1.35 kg/m³ at GWD 20 cm. WP(I+R) fell with increasing GWD. The ANOVA results (Table 4) showed that the WP(I+R)s at GWD 20–190 cm were significantly different from the WP(I+R) at GWD 1000 cm at $P_c = 95\%$, but there were no significant differences between WP(I+R)s at GWD 20–150 cm and 60–190 cm. WP(I+R) at shallower groundwater depths was higher than that at deeper groundwater depth in lowland rice production.

Water balance components

Figure 6 shows water balance components (and standard errors) under different GWDs. The rainfall value was constant. Irrigation input ranged from 349 mm at groundwater depth of 20 cm to 375 mm at 1000 cm. Irrigation at GWD 20 cm was significantly different from that at 60–1000 cm, but there were no significant differences between among 60 to 1000 cm GWDs at $P_c = 95\%$. Irrigation at 1000 cm GWD was significantly different from that at 20–190 cm at $P_c = 95\%$. Shallower groundwater depth saved irrigation input.

Evaporation was almost the same value, although evaporation at 20 cm GWD was significantly different from that at 60–1000 cm at $P_c = 95\%$. Transpiration at 1000 cm GWD was significantly lower than that at 20 to 190 cm. Percolation ranged from 163 mm at 20 cm GWD to 197 mm at 1000 cm GWD.

Percolation at 20 cm GWD was significantly lower than that at 20–1000 cm, and percolation at 1000 cm GWD was significantly higher than that at 20–190 cm at $P_c = 95\%$. Percolation increased with increasing GWD. The total water input at 20 cm GWD was small because of less irrigation input. The total water input at 1000 cm GWD was also small,
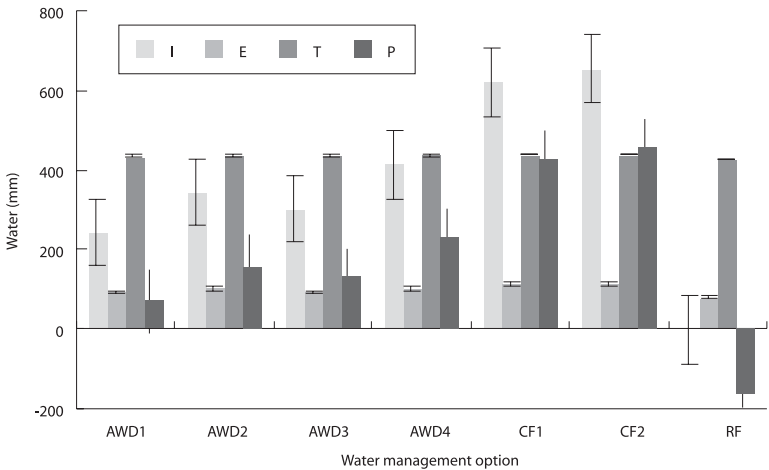

Figure 5. Water balance components under different water management options. See text for details of options. Vertical and capped lines are standard errors.

but because of less capillary rise. The total water input at 60–190 cm GWD was the same.

Table 5. Mean of yield and total water productivity (WP(I+R)) under different water management options (WMO)

WMO	Yield (kg/ha)	WP(I+R) (kg/m^3)
FI −10 kPa	4288 a	0.59 a
FI −15 kPa	4159 b	1.01 b
FI −20 kPa	4068 c	1.24 c
FI −30 kPa	3975 d	1.39 d
FI −50 kPa	3862 e	1.39 d
RF	3566 f	1.38 d

Note: statistical differences (P ≤ 0.05) among numbers in the same column are indicated by different lower-case letters.

Effects of water-saving irrigation and groundwater depths: the aerobic rice system

The ANOVA results showed that the major water balance components (percolation, transpiration, evaporation, and irrigation), grain yield, and water productivity were significantly affected by WMO, GWD, and their interactions at P_c = 95%.

Effects of water-saving irrigation

Grain yield

Table 5 shows the means of grain yields under different WMOs. The mean yield ranged from 3566 kg/ha in RF to 4288 kg/ha at the FI −10 kPa threshold level.

Yield decreased from the FI −10 kPa threshold level to −50 kPa and then to rainfed. The ANOVA results (Table 5) show that yields among different irrigation threshold levels and rainfed conditions had significant differences at P_c = 95%. Average irrigation yield was 12.4% higher than rainfed yield, and yield at the −10 kPa irrigation threshold level was 16.8% higher than rainfed yield.

Water productivity

Table 5 shows total water productivity under different WMOs. WP(I+R) ranged from 0.59 kg/m^3 at the −10 kPa irrigation threshold level to 1.38 kg/m^3 in RF. The ANOVA results (Table 5) show no significant differences in water productivity between WP(I+R)s at the −30 and −50 kPa flush irrigation threshold levels and RF. WP(I+R)s at the −10, −15, and −20 kPa flush irrigation threshold levels were significantly different at P_c = 95%, and were significantly different from that at the −30 and −50 kPa flush irrigation threshold levels and RF. Flush irrigation at the threshold levels of −10 and −15 kPa had higher water productivities and yields. Although RF gave high water productivity, yield was low.

Water balance components

Figure 7 shows water balance components (and standard errors) under different WMOs. There were significant differences among the irrigation water management options. Irrigation ranged from 296 mm at −50 kPa to 1682 mm at the −10 kPa threshold level.
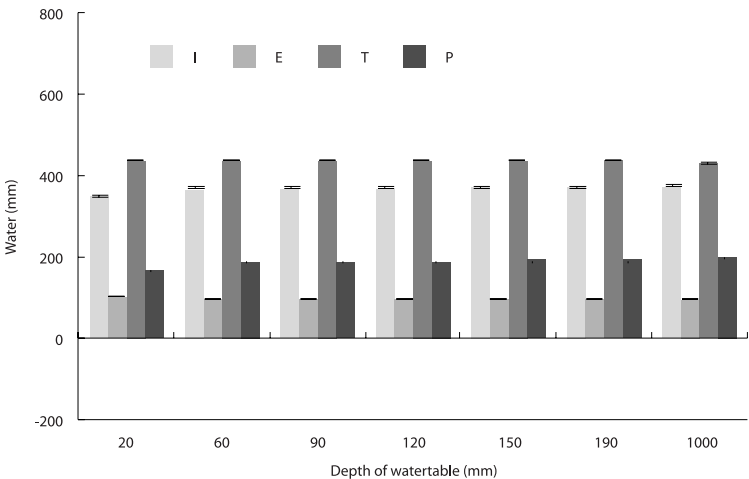

Figure 6. Water balance components under different groundwater depths. Vertical and capped lines are standard errors.

Evaporation ranged from 146 mm in rainfed to 181 mm at the –10 kPa irrigation threshold level. Transpiration ranged from 200 mm in rainfed to 238 mm at the –10 kPa irrigation threshold level. Evaporation and transpiration differences were not large. Percolation ranged from 226 mm at the –50 kPa threshold level to 1580 mm at the –10 kPa threshold level. Percolation in the RF treatment was negative, which indicated that the soil water supply (capillary rise) was used to satisfy evapotranspiration (ET). The trends of total water input under different water management options were the same as those of irrigation input.

Effects of groundwater depths

Grain yield

Table 6 shows the means of grain yields under different GWDs. The mean yield ranged from 2654 kg/ha at GWD 1000 cm to 4645 kg/ha at GWD 20 cm. Yield fell with increasing GWD. The ANOVA results (Table 6) showed that the yields among different GWDs had significant differences at $P_c = 95\%$. Yield at GWD 20 cm was 43% higher than that at 1000 cm. Average yield at shallower GWDs (20–120 cm) was 39.2% higher than at deeper GWD (1000 cm).

Water productivity

Table 6 shows total water productivity under different GWDs. WP(I+R) ranged from 0.08 kg/m³ at GWD 1000 cm to 1.74 kg/m³ at GWD 30 cm. The ANOVA results (Table 6) showed that WP(I+R)s at

GWD 30 and 60 cm were significantly different from those at GWD of 90–1000 cm. There were significant differences among the WP(I+R)s at GWD 90–1000 cm. Water productivity at shallower GWDs was much higher than that at deeper ones. Water productivity fell with increasing GWD.

Table 6. Mean of yield and total water productivity (WP(I+R) under different groundwater depths

GWD (cm)	Yield (kg/ha)	WP(I+R) (kg/m³)
30	4645 a	1.74 a
60	4506 b	1.74 a
90	4250 c	1.42 b
120	4069 d	1.29 c
150	3949 e	1.07 d
190	3832 f	0.82 e
1000	2654 g	0.08 f

Note: statistical differences ($P \leq 0.05$) among numbers in the same column are indicated by different lower-case letters.

Water balance components

Figure 8 shows water balance components (and standard errors) under different GWDs. Percolation, transpiration, evaporation, and irrigation were significantly affected by different groundwater depths. Rainfall was not affected and kept the same value. Irrigation input ranged from 0 mm at GWD 60 cm to
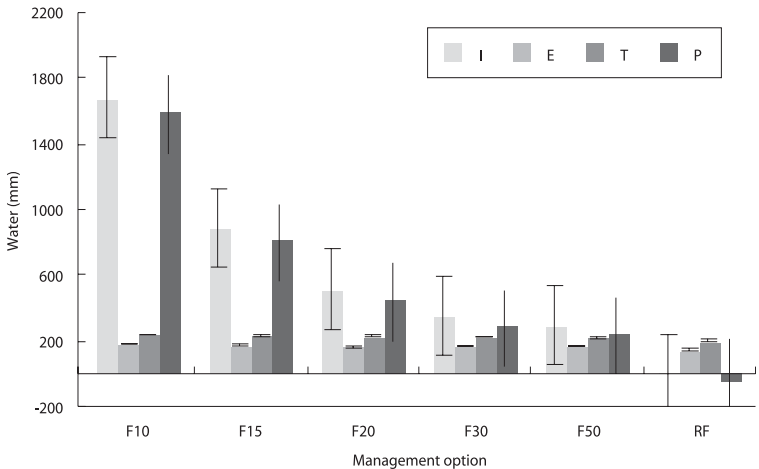

Figure 7. Water balance components under different water management options. See text for details of options. Vertical and capped lines are standard errors.

2371 mm at GWD 1000 cm. There were no significant differences in irrigation between 30 and 60 cm GWD at P_c = 95%. Irrigation at 30 and 60 cm GWD was significantly different from that at 90–1000 cm. Irrigation increased with increasing GWD. Shallower groundwater saved irrigation input.

Evaporation was almost the same for GWD 30–190 cm. Evaporation at GWD 1000 cm was higher than that for shallower depths. Transpiration ranged from 154 mm at 1000 cm GWD to 270 mm at 30 cm. Transpiration fell with increasing groundwater depths.

Percolation ranged from 121 mm at 90 cm GWD to 2324 mm at 1000 cm. Percolation at shallower groundwater depth was significantly lower than when the top of the watertable was deeper (1000 cm). Percolation increased with increasing groundwater depths. The total water input at 30 and 60 cm GWD was small because of less irrigation input. The total water input was large at 1000 cm of groundwater depth.

Discussion and conclusions

Agreement is relatively close between simulated and measured values of crop and soil variables. The majority of the statistical parameters and graphical comparisons show that the ORYZA2000 model is sufficiently accurate in simulating, over time, crop growth variables and yield, and soil water dynamics for inbred rice and aerobic rice under rainfed and irrigated production situations in the region. The model

can be used to support field experiments in exploring the effects of management interventions (such as water management, fertiliser application, and plant density) and environmental conditions (weather, depth of the groundwater table) on the growth and development of inbred and aerobic rice varieties and water balance, with quantifiable errors of simulation.

For the puddled rice system in the northern part of the study area, irrespective of groundwater depth, all AWD irrigation gave yields similar to those of continuous flooding. AWD saved 30–60% of irrigation water, mostly because of reduced percolation. It had little effect on evaporation and transpiration. AWD irrigation increased total WP by 30–60%. Yields had no significant differences from 20 to 190 cm GWD, but all the yields at 20–190 cm of groundwater depth were significantly different from the yield at groundwater depth of 1000 cm. Shallower GWDs gave significantly higher grain yields than deeper GWDs in lowland rice production.

For the aerobic rice system in the southern part of the study area, irrespective of groundwater depth, yield decreased from the –10 to –50 kPa irrigation threshold, and so did the irrigation input. The yield of rainfed was the lowest. There was a 10% yield loss from the –10 to –50 kPa threshold, but an 80% irrigation water saving from the –10 to –50 kPa threshold, mostly because of reduced percolation. WP increased 60% from the –10 to –50 kPa irrigation threshold; WP was the lowest at the –10 kPa irriga-
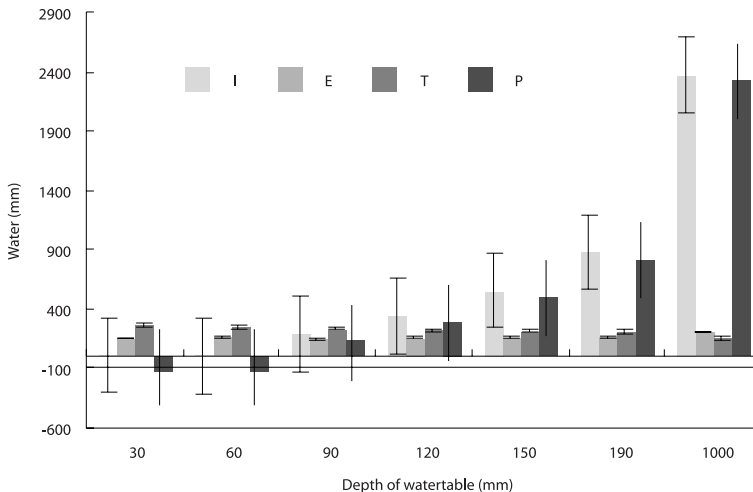

Figure 8. Water balance components under different groundwater depths (vertical and capped lines are standard errors)

tion threshold. There were falling trends in yield and transpiration from 30 to 1000 cm GWD for all water management options, and the differences of yield and transpiration increased from the –10 to –50 kPa irrigation threshold, and to rainfed conditions.

The results indicate that AWD and aerobic rice maintain high yields and save irrigation water with shallower groundwater depths in the area. This highlights the importance of water-saving techniques and shallower groundwater depths for increasing rice yields and water productivity.

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Tracking fallow irrigation water losses using remote-sensing techniques: a case study from the Liuyuankou Irrigation System, China

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Abstract

Efficient water use is the key for sustainable management of water resources. Currently, water resources are not managed efficiently, especially in developing countries, due to the non-availability of reliable information about the actual water used by different agricultural crops within a large irrigation system or at the basin scale. Therefore, an estimation of spatially distributed crop water consumption is important and challenging for determining water balance at different scales to promote efficient management of water resources. The use of remote sensing data can resolve difficulties in determining water balance due to scientific developments in the calculation of actual evapotranspiration. In this study, seven TERRA/MODIS satellite images were acquired on different dates (6 April, 31 May, 12 June, 12 July, 23 August, 22 September and 24 October) during the summer cropping season of 2002 over Liuyuankou Irrigation System (LIS) located along the Yellow River basin of China.

The surface energy balance algorithm for land (SEBAL) was applied to MODIS sensor data for the estimation of crop water requirement. The actual evapotranspiration (ET_a) was integrated for 24 hours on a pixel-by-pixel basis from the instantaneous evapotranspiration (ET). Later, temporal integration (April–October 2002) was done to get the seasonal actual evapotranspiration (ET_s) map of the LIS area.

Volumes of crop water consumption at different scales were compared through statistical analyses. The comparison provided better decision-making for identifying, at different spatial scales in an irrigation system, areas (e.g. fallow lands) that have high non-beneficial evapotranspiration. The result showed a unique combination of derived ET_a from different MODIS images for water consumption in the LIS. The results were further compared with the crop potential evapotranspiration (ET_c) calculations at a meteorological station in the LIS. This showed a deviation of –5% between ET_a and ET_c. which is within an acceptable range. However, the accuracy of this comparison of modelled ET_a against measured data of ET_c needs to be considered with respect to scale. Modelled area data were derived from discrete areas of one square-kilometre (the spatial resolution of a MODIS pixel for thermal bands) and would therefore contain reflectance attributes from many different physical mediums (mixed spectral signatures) and a resulting combined evapotranspiration rate. The discussion provides the research orientation for ET assessment at different scales and its further implications in applied research for water management aided by satellite images.

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用遥感技术跟踪灌溉水量损失：中国柳园口灌区典型研究

摘要：高效用水是水资源可持续管理的关键。目前，对水资源的管理效率不高，特别是在发展中国家，其原因是在大型灌区或流域尺度上缺乏不同作物实际用水的可靠的信息。因此，对在空间上分布的作物耗水量的估计对于确定不同尺度上的水平衡，促进水资源的高效管理是十分重要的且具有挑战性。由于在计算实际蒸腾量方面的科学发展，遥感数据的应用可以解决确定水平衡时遇到的困难。这项研究用了坐落在黄河边上柳园口灌区（LIS）2002年夏季作物种植季节不同时间（4月6日、5月31日、6月12日、7月12日、8月23日、9月22日和10月24日）的7个TERRA/MODIS卫星映像资料。土地地表能量平衡法（SEBAL）和MODIS遥感数据被用来来确定作物需水量。实际的蒸腾量(ETa)是24小时各单元实时蒸腾量(ET)之和。而后，按时间进行累计（4月到10月）获得柳园口灌区季节的实际蒸腾量（ETs）图。通过统计分析，计算处理不同尺度上的作物耗水量。通过比较可以为辨识灌溉系统内不同空间尺度上无效蒸腾量高的区域（如休闲地）提供较好决策。结果显示，柳园口灌区耗水从不同的MODIS映像获得的ETa有独特的组合。这个研究结果进一步与在柳园口灌区用气象站资料计算出的作物潜在蒸腾量（ETc）进行了比较。结果显示ETa和ETc之间的差别为−5％，这个误差在可以接受的范围内。然而，模型计算的ETa与观测的ETc相比较的精确度需要在相应的尺度范围进行考虑。模型的面积数据是从1平分公里的离散面积上得到的（MODIS热带单元空间法），因此可能包含多个不同物理中间值和一个组合的蒸腾率。讨论部分提供了用于不同尺度ET评估的研究方向和出卫星图像辅助的水管理应用研究意义。

Introduction

The world's thirst for water is likely to stay as one of the most pressing resource issues of the 21st century. Agriculture is the largest consumer of water in the Asian region as compared to other sectors i.e. domestic, municipal, industrial and environmental. However, the water-use efficiency of agriculture is very low. The improvement of water-use efficiency requires a complete understanding of all the terms of the water balance at various scales such as field, farm, irrigation system and basin level. The dominant aspect of water balance is evapotranspiration (ET), which is one of the most difficult parameters to measure in the field. A number of researches undertaken in the past have estimated reference ET from meteorological data and converted this to actual ET. The major disadvantage of this approach is that most methods generate only point values, resulting in estimates that are not representative of larger areas. These methods are also based on crop factors under ideal conditions and cannot therefore represent actual crop ET.

The use of remote-sensing techniques for the estimation of the water evaporation component of water balance is achieved by solving the energy balance of thermodynamic fluxes at the surface of the earth. The use of these remote-sensing techniques has become increasing popular since 1990 due to the relatively low cost of data collection — \$0.03/ha for irrigated lands (Sakthivadivel et al. 1999).Various methods for the estimation of actual evapotranspiration have been developed by combining satellite images and ground meteorological data for large areas (Vidal and Perrier 1989; Choudhury 1994; Granger 1997). Another method of estimating actual ET is the surface energy balance algorithm for land (SEBAL). SEBAL is a thermodynamically based model, using the partitioning of the fluxes of sensible heat and latent heat of vaporisation.

SEBAL was originally developed in Spain and Egypt with Landsat 5TM in 1995 by Bastiaanssen (1995). Further applications to irrigation performance were later found for the same sensor in Argentina (Roerink et al. 1997). Water consumption of large irrigation systems has been addressed also with NOAA AVHRR in Pakistan (Bastiaanssen et al. 1999, 2001). Farah (2001) studied modelling of evaporation under various weather conditions in the Navaisha Basin, Kenya. Farah's results extended SEBAL calculations of NOAA AVHRR under clouds with a Penman–Monteith approach supported by a Jarvis–Stewart type model. Combinations of Landsat and NOAA are reported in Timmermans and Meijerink (1999) where Landsat 5TM was used, and in Chemin and Alexandridis (2001) where Landsat 7ETM+ was used. Later, Hafeez (2003) applied SEBAL for the estimation of seasonal actual evapotranspiration using TERRA/ASTER, TERRA/MODIS and Landsat 7ETM+ sensors in UPRIIS, Philippines.

The main constraint in using remote sensing-based models is that ET_a is calculated on only the satellite overpass days. The non-availability of cloud-free images, intensive computing procedure and cost also pose major constraints in processing visible/thermal-infrared satellite images for daily ET_a estimation. Temporal integration strategies have to be used in order to interpolate the missing satellite data and obtain the integrated ET_a information for a season, so that ET results can be used in water balance studies.

The primary aim of the study reported here was to calculate the daily actual evapotranspiration in the Liuyuankou Irrigation System (LIS) area, using the SEBAL model applied to a remote sensing TERRA/MODIS sensor. A second objective was to estimate seasonal actual evapotranspiration of the LIS area for the summer season of 2002. These results were integrated with a MODFLOW-based water balance of the LIS which will be reported on separately.

Description of the Liuyuankou Irrigation System

LIS is located in northeastern China, in Kaifeng County of Henan Province (Figure 1). Irrigation for crop production is met by water drawn from the channels diverted from the Yellow River, mainly in the northern area of LIS (situated north of (above) the railway line and hereinafter known as ARL), as well as by groundwater pumping in the southern area of LIS (situated south of (below) the railway line and hereinafter known as BRL). The total area of LIS is 55,512 ha with a net irrigated command area of 40,724 ha. The Liuyuankou major canal is located in the upper part of the irrigation district, and feeds three main canals and fourteen branch canals. Mean annual temperature is 14.1°C and mean annual precipitation 627 mm (of which 70–80% falls during June–September). Mean annual evaporation is 1316 mm. Maximum evaporation occurs from March to August. The major crops cultivated in the LIS

include winter wheat, summer maize, cotton, rice and soybean.

Materials and methods

Satellite data

MODIS is the key instrument aboard the TERRA (EOS AM-1) satellite, which began operation in March 2000. TERRA/MODIS views the entire earth surface every 1–2 days, acquiring data in 36 spectral bands (different wavelengths of electromagnetic radiation). The bands have 250–1000 m spatial resolution. An overview of the sensor is provided in Table 1. This study uses seven MODIS images of the LIS area acquired on different dates (see details in Table 1) to estimate seasonal actual evapotranspiration for the summer season of 2002.

Specificity of porting SEBAL to MODIS sensor

Acquisition of image data 'level 1B' (L1B) was done through the Red Hook Eros Data Center website using the ftppull file transfer protocol. Extraction of the binary file was performed for two bands (1 and 2), five short-wave infrared bands (3, 4, 5, 6 and 7) and two thermal bands (31 and 32). A subset image for the study area was created from the whole image of China for better visualisation and geo-referencing. The L1B data were already calibrated for radiometric variations, while geo-referencing was done in TM/WGS/84/Zone 50 with a root mean square error (RMSE) of less than 1 pixel.

The pre-processing parameters required for SEBAL include the normalised difference vegetation index (NDVI), emissivity, broadband surface albedo, and surface temperature for both sensors. The NDVI
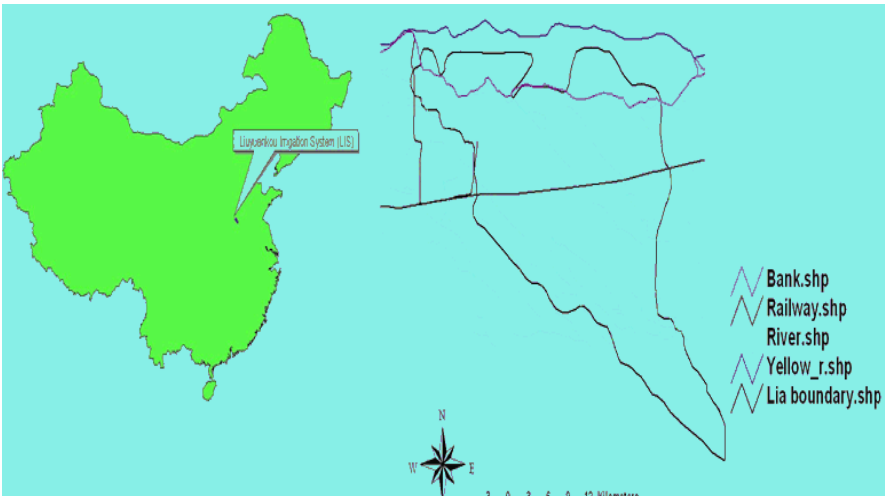
Figure 1. Layout of Liuyuankou Irrigation System (LIS) in China

Table 1. Overview of TERRA/MODIS sensor and details of satellite image used in the study

Sensor	Dates in 2002 of satellite images used	Subsystems	Number of bands	Spectral range (μm)	Spatial resolution (m)
TERRA/MODIS	6 April, 31 May, 12 June, 12 July 23 August, 22 September, 24 October	VNIR SWIR SWIR TIR	2 5 11 16	0.62–0.876 0.459–2.155 0.405–0.965 3.66–14.385	250 × 250 500 × 500 1000 × 1000 1000 × 1000

was calculated from bands 1 and 2 of MODIS data, and the broadband albedo was calculated using weighing factors of all visible, near infrared and short wave infrared bands of MODIS (Liang et al. 1999). Surface emissivity of the sensor was calculated from the NDVI of the sensors. Surface temperature from MODIS sensors was calculated from thermal bands 31 and 32 using the split-window technique described in Wan (1999).

Running SEBAL

Calculation of the net incoming radiation and the soil heat flux were done after Bastiaanssen (1995), while the later development of Tasumi et al. (2000) was incorporated to determine the sensible heat flux. However, to calculate the first temperature difference between air and soil for the 'hot' pixel (i.e. where the latent heat flux is assumed null), a first estimation of the air density was required. This was achieved by generalising meteorological data on relative humidity and maximum air temperature from a meteorological station at the time of satellite overpass. Iterations of sensible heat flux were conducted five times. Operational observation showed that this method does not stabilise the air–soil temperature difference as fast as the earlier method in Bastiaanssen (1995). In SEBAL, manual sampling of hot pixel values of the previous iteration's output image files are required before the next iteration can be done, which is a practical constraint in using this technique. This constraint can be resolved by automation (after hot pixel identification) of the data collection. The sensible heat flux can be improved by repeating the iteration five times, but this process is time and space consuming.

The ET is calculated in SEBAL (Tasumi et al. 2000; Hafeez 2003) from the instantaneous evaporative fraction, Λ, and the daily averaged net radiation, R_{n24}. The latter has to be transformed from W/m^2 to mm/day by the T_0-dependent latent heat of vaporisation equation inserted in the main equation (Equation 1):

$$ET_{24} = \Lambda\{R_{n24}[(2.501 - 0.002361 T_0)10^6]\} \quad (1)$$

where ET_{24} = daily ET actual (mm/day)

R_{n24} = average daily net radiation (W/m^2)
T_0 = surface temperature (°C).

The evaporative fraction, Λ, is computed from the instantaneous surface energy balance at the moment of satellite overpass for each pixel (Equation 2):

$$\Lambda = \lambda E/R_n - G_0 = \lambda E/\lambda E + H_0 \quad (2)$$

where λE = latent heat flux (the energy allocated for water evaporation) (λ can be interpreted in irrigated areas as the ratio of actual evaporation to crop potential evaporation. It is dependent on the atmospheric and soil moisture condition equilibrium.)

R_n = net radiation absorbed or emitted from the earth's surface (radiative heat) (W/m^2)
G_0 = soil heat flux (conduction) (W/m^2)
H_0 = sensible heat flux (convection) (W/m^2).

The ET_a calculation through remote sensing on specific dates provided a good indication of its spatial distribution in the irrigation system. However, this information could not be used directly, as ET_a directly depends upon weather conditions and water availability in the field, which varies from day to day. It was therefore necessary to simulate daily values to get an accurate estimation of seasonal ET_a. A larger sample of timely ET observations is necessary to obtain an accurate result and to adjust the daily fluctuation of ET_a for integration of seasonal ET_a. As proposed by Tasumi et al. (2000), missing values of ET_a could be obtained by daily calculation of reference evapotranspiration (ET_0) using the modified Penman–Monteith method. Temporal integration was undertaken in four steps: (1) determination of the period represented by each satellite image, e.g. selecting the 6 April 2002 image to represent the month of April etc.; (2) computation of ET_0 using the modified Penman–Monteith method for the whole period represented by each image (average monthly ET_0 values collected from Huibei meteorological station, summarized in Table 2); (3) computation of K_m values for each period as shown in Table 3; and (4) computation of cumulative seasonal ET_a using Equation 3:

$$ET_S = \sum_{i=1}^{n} (ET_a)(K_m)_i \quad (3)$$

where ET_a = actual daily ET value computed by SEBAL for each pixel of image 'i' (mm)

K_m = multiplier for ET for the representative period

n = number of satellite images processed
ET = seasonal ET (mm).

Results and discussion

Daily meteorological data were collected from the Huibei weather stations and used to calculate ET_0 through the modified Penman–Monteith equation

Table 2. Average ET_o and cumulative ET_o values representing meteorological stations in the Liuyuankou Irrigation System, northwestern China

ET	6 April	31 May	12 June	12 July	23 August	22 September	24 October
Cumulative ET_o (mm)	97.95	96.77	138.9	117.3	106.33	96.45	72.66
Average ET_o (mm)	3.53	4.92	6.16	5.72	4.23	2.23	1.93

Table 3. Values of K_m for the summer season 2002 in the Liuyuankou Irrigation System, northwestern China

	1–30 April	1–31 May	1–30 June	1–31 July	1–31 August	1–30 September	1–30 October
K_m	27.75	19.67	22.55	20.51	25.14	43.25	37.65

(Allen et al. 1998). ET_o was converted into potential crop transpiration, ET_c, by multiplication with the crop coefficient K_c ($ET_c = K_c \times ET_o$). Based on the actual cropping calendar, the weighted crop coefficient K_c for different satellite overpass dates was used in this study. The major crops in the LIS were rice, maize and cotton.

In this study, the pixel values of ET_a, calculated through SEBAL, in the area surrounding Huibei meteorological station were compared with the measured evaporation through class A pan (E_{pan}), estimated ET_o and crop evapotranspiration (ET_c) from the Huibei meteorological station for the summer season of 2002 in LIS as shown in Figure 2. There is a significant difference in ET values obtained from remote sensing and classical techniques based on weather station data. The former provides spatial distribution results, whereas the latter provides only point values.

E_{pan} indicates the evaporation from water bodies. As validated in Figure 2, E_{pan} value from Huibei meteorological station was always higher (on average 26%) than ET_a values for all seven image acquisition dates during the season. For pixels assumed to be under a cropping area, the estimated ET_a was on average 11% and 5% lower than the average ET_o and ET_c calculated from meteorological station data. The comparison provides an indication of the amount of confidence that can be placed on the values of ET_a derived from the remote-sensing images. The ET_a is estimated from all the physical media within one pixel (250 m as in the case of MODIS), which might have mixed spectral signatures of roads, settlements, water bodies, and rice fields. Due to the large pixel size of MODIS (250 m), it is difficult to absolutely compare such information with the classical point data from meteorological data, even though Figure 2 shows a

good trend regarding the accuracy of ET_a derived from the SEBAL model.
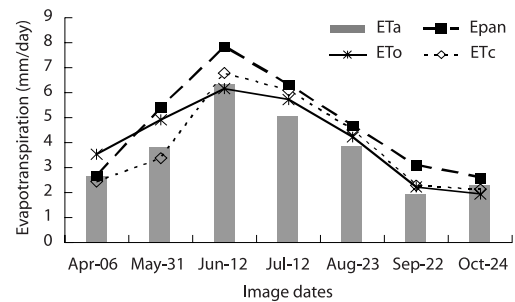
Figure 2. Comparison of ET_a of rice pixels with E_{pan}, ET_o, and ET_c, at Huibei weather station for the summer season 2002 in LIS

Nevertheless, the accuracy of this comparison of modelled against measured data needs to be considered with respect to scale. Modelled area data were derived from discrete areas of one square-kilometre (spatial resolution of a MODIS pixel for thermal bands) and would therefore contain reflectance attributes from many different physical media (mixed spectral signatures from rice fields, bare fields and roads) and a resulting combined evapotranspiration rate. Comparison between the modelled data and the point-based measured data from class A pans or meteorological stations introduces the possibility of scale-related errors. Even though a comparison of ET_a with E_{pan}, ET_o and ET_c does not bring sufficient absolute elements for validation, it does contribute to a consistency cross-checking of the method of ET_a calculation from SEBAL. The comparisons show similar trends in ET in the time domain of the summer season 2002.

The integration of daily ET_a raster maps was done using the straightforward method described in the

temporal integration part of the previous section. The seasonal actual evapotranspiration (ET_s) map on a pixel-by-pixel basis was produced through integration of all daily ET_a images for the summer season 2002. The statistics of ET_s and volume of water consumption for different areas in the LIS during the summer season 2002 (1 April–31 October) are summarised in Table 3. Results show that ARL area has a higher volume of water consumption through actual evapotranspiration than the BRL area. This is mainly due to higher ET from shallow watertables caused by inefficient surface water irrigation and lateral seepage of river water. The comparison provided better decision-making for crop water requirements in the ARL and BRL areas for this irrigation system.

From a water management perspective, the most important model output of SEBAL was the spatially distributed estimation of the seasonal actual evapotranspiration (ET_s) which was later used with a MODFLOW model of the area. These volumes were cross-validated by the water balance of the LIS provided by Khan et al. (2004). For example, Figure 3 depicts a range from 300 mm to 855 mm of ET_s in the LIS region for the summer season of 2002.

Low seasonal actual evapotranspiration is modelled for the bare fields and settlements, while the irrigated areas range from medium to high ET_s. The agricultural areas in the LIS just above the railway line (ARL) have higher ET_s values due to a shallow watertable, lateral seepage from the Yellow River and a network of leaky irrigation canals. Higher ET_s values are indicated by darker blue colour in Figure 3.

The areas below the railway line (BRL) have lower ET_s values because the watertable is quite deep and

Table 3. Seasonal evapotranspiration (ET_s) in LIS

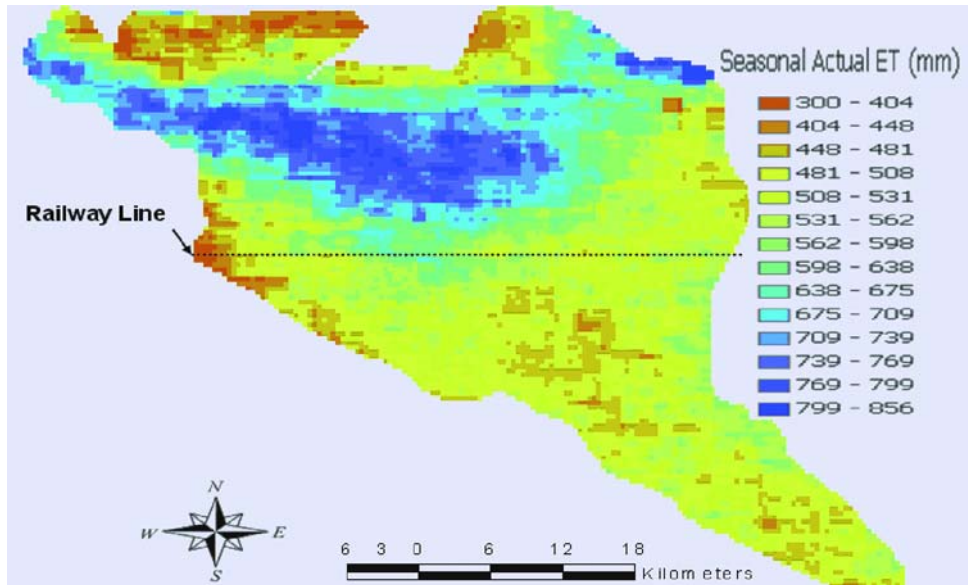| Area	Area (ha)	Minimum ET_s (mm)	Maximum ET_s (mm)	Mean ET_s (mm)	Standard deviation (mm)	Volume (million m³)
Above rail line (ARL) area	27,187	300.2	852.8	577.1	160.3	170.9
Below rail line (BRL) area	28,325	327.3	751.3	537.7	124.6	147.6
LIS	55,512	300.2	852.8	557.4	160.7	317.3

Figure 3. Seasonal actual evapotranspiration (ET_s) map of the Liuyuankou Irrigation System, northwestern China using MODIS sensor (250 m) for the summer season of 2002

there is no surface water irrigation network. Lower ET_s values are coloured yellow in Figure 3. The ET_s map further shows a spatial gradient of decreasing evapotranspiration from the northern (ARL) parts towards the southern parts (BRL) of the irrigation system. In Figure 3, the irrigated rice fields (blue) can be differentiated from the non-irrigated fields (red) at a spatial resolution of 250 m.

The histograms of ET_s for LIS, ARL and BRL from an image representing the whole summer season of 2002 over the irrigation system of LIS are shown in Figure 4. The histogram of ET_s shows the water consumption pattern has many peaks with the main peak features in a covered area is 518 mm @ 1531 ha for BRL area, 516 mm @ 1087 ha for LIS area and 745 mm @ 437 ha for ARL area.
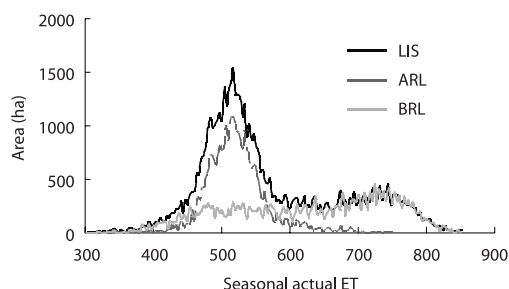

Figure 4. Sensor histogram of seasonal actual evapotranspiration (mm)

Conclusion

This study focused on the evaluation of multi-temporal MODIS data to calculate actual and seasonal evapotranspiration, applying the SEBAL model. Optical satellite imagery and the SEBAL algorithm provide estimates of spatially distributed ET_a on the days of satellite overpass. The spatial patterns could generally be explained by the cropping patterns observed in the field. The problem of spatially distributed seasonal ET_a estimation can be overcome by integrating daily ET_a from satellite images acquired on different dates in a cropping season with the reference evapotranspiration. The seasonal actual evapotranspiration provides a good indicator of crop water consumption throughout the study area. A comparison of ET_a estimated from SEBAL with potential crop evapotranspiration (ET_c) measurements showed a deviation of –5%, which is within an acceptable range. The possible reason for deviation of the ET_a estimates using the MODIS sensor is pixel size for small agriculture fields, because the thermal bands of MODIS provide surface temperature over one square kilometre. Estimation of actual ET from remote sensing indicated relatively good accuracy and potential for use in the water balance and water productivity of the LIS for the summer season of 2002. In the next step of this study, volume of water consumed for different land use types is being estimated. This will provide information about the volume of water lost through fallow land in the LIS. The quantification of non-beneficial ET will help irrigation managers to develop new strategies for water saving from the fallow land, which will help towards sustainable management of water resources in the LIS area.

Acknowledgment

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Implications of environment and institutions for water productivity and water savings: lessons from two research sites in China

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Abstract

This paper is based on research conducted at two irrigation systems in China situated in strikingly different environments. The Zhanghe Irrigation System (ZIS) is located just north of the Yangtze River approximately 200 km west of Wuhan. The Liuyuankou Irrigation System (LIS) lies south of the Yellow River, just to the east of Kaifeng City. ZIS is situated in hilly terrain with clay loam soil and relatively abundant water resources but increasing competition for water for other uses. LIS is situated in flat terrain with loam soil and good groundwater resources in the physically water-scarce Yellow River Basin. What can be learned by contrasting these cases? The lessons about water productivity and savings form part of a changing trend in thinking about irrigation that considers the analysis of scales, multiple uses, and practices of irrigation in the context of water scarcity.

The paper presents institutional and management arrangements and contrasts water management strategies at farm, system and sub-basin level and shows how these have led to water savings and increases in water productivity. In the water-rich environment of ZIS, farm and canal management of water is much more precise than in the water-scarce environment of LIS. Yet both systems are close to their water-saving potential. Both systems have experienced remarkable increases in irrigation water productivity over time, largely from increases in crop yields, but in the case of ZIS also from changes in management. Controlling supplies and reallocating as much as possible to non-agricultural uses while assuring an adequate supply for agriculture is extremely important in ZIS where water productivity per unit of irrigation supply is the key measurement. At LIS, because of water resource scarcity, there is evidently scope for reducing evaporation from raised watertables. Thus, water productivity per unit of evapotranspiration is the key measurement. We suggest that design improvements at LIS be targeted to reduce any non-beneficial evaporation, a recommendation that holds across many water-scarce environments globally.

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环境和体制对水分生产率和节水的影响
－从中国两处试验研究获得的启示

摘要：这篇论文基于在中国两个环境完全不同的灌溉系统开展的研究工作。漳河灌溉系统（ZIS）位于长江以北，大约在武汉市以西200公里的地方。柳园口灌溉系统（LIS）坐落在黄河以南，东临开封市。漳河灌区的地形为山地梯田，土壤为粘壤土，水资源相对丰富，但其他用水户的用水竞争与日俱增。柳园口灌溉系统坐落在平原地区，土壤为壤土，在地下水资源条件良好但缺水的黄河流域。对比这两个相反的例子会得到什么结果呢？水分生产效率和节水的启示引发了思考灌溉变化趋势，包括考虑分析尺度，多目标应用和在缺水条件下的灌溉实践 。论文介绍了体制和管理方面的安排以及在农田、灌溉系统和子流域上相互对比的水管理策略，展示了这些因素如何促进实现节水和增加水分生产效率。在水资源丰富的漳河灌溉系统，农田和渠道的水管理要比缺水的柳园口灌溉系统精确的多。这两个灌溉系统还具有节水潜力。这两个灌溉系统都经历了灌溉用水生产效率随时间的显著提高，大部分来源于作物产量的增加，但对于漳河灌区水分生产效率的提高还来源于在管理方面的改善。在漳河灌区，控制供水并尽可能将更多的水重新分配给非农业用户，同时保障为农业提供允足的水源是极其重要的。在漳河灌区，单位灌溉水量的水分生产率是主要的衡量指标。由于缺水，在柳园口灌溉系统通过减少由于地下水位升高而产生的蒸发是显而易见的事。因此，单位蒸腾量水分生产效率是主要的衡量指标。我们建议，在柳园口灌溉系统改善设计的目标是减少所有的无效蒸发，这一建议对全世界许多缺水的环境条件都实用。

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1 Introduction

Between 1999 and 2005, detailed studies of two irrigation systems were carried out in China.[2] The Zhanghe Irrigation System (ZIS) is located just north of the Yangtze River near the city of Jinmen, about 200 km west of Wuhan (Figure 1). The Liuyuankou Irrigation System (LIS) lies south of the Yellow River, just to the east of Kaifeng City.

Figure 1. Locations of study sites: Zhanghe Irrigation System (ZIS) and Liuyuankou Irrigation System (LIS)

The different physical and institutional contexts for each system provided an excellent opportunity to gain valuable insights into water savings, water productivity, institutions and incentives, irrigation operations and infrastructure. Studies were carried out at different scales — field, farm, household, canal level, system and sub-basin level — providing different perspectives on each of these issues. This paper compares and contrasts the two systems to draw out important lessons for stakeholders of the systems and, more widely, for all those involved in improving irrigation for enhanced water productivity.

The paper is organised as follows. Sections 2 and 3 describe the physical and the institutional context and settings for the two research sites. Section 4 discusses the incentives to save or reallocate water, and the sixth through eighth sections the scope for water saving and gains in water productivity. Section 9 is concerned with scale issues in water-resource management. Section 10 presents strategies for improved water-

resource management in ZIS and LIS. The final section, Rethinking irrigation, draws some general conclusions about irrigation that emerge from this study.

2 Comparing ZIS and LIS: the physical context

ZIS lies in the Yangtze River Basin which, from an annual, basin-wide perspective, has ample water, but locally and in certain seasons physical scarcity may be an issue. The basin is 'open'[3] in that not all water is allocated across uses, one of the reasons that China is considering a project for south–north water transfer. Downstream users will not readily notice whether or not ZIS depletes more water. On the other hand, the ZIS storage systems are important in protecting the basin from floods.

LIS is situated within the Yellow River Basin, a chronically stressed river. This basin is 'closed', in the sense that all water is allocated across uses, and there is arguably not enough water to meet environmental-flow requirements. If LIS depletes more water, other users within the basin will be affected, and it will be a contentious issue in river basin management.

ZIS is situated in hilly terrain that gradually flattens to the floodplains of the Yangtze. At ZIS, most drainage water readily finds its way back to the natural drainages and river system where it can be captured and used or reused, and is classified as a natural recapture zone.[4] The soil is clay loam with a relatively low percolation rate. Farmers acting on their own and the irrigation authorities in the area have taken advantage of this situation and built thousands of reservoirs and ponds of various sizes to capture drainage flows. Floods far overshadow water scarcity as an issue in the area. For safety, reservoirs are often drawn down to low levels in the flood season, a practice that at times stresses the agricultural system. Although not a topic of this study, water

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3 Open basins are those where useable outflow exists (in excess of acceptable environmental-flow levels) at the end of the basin and there is additional water for allocation across uses. Closed basins are those where all water is already allocated to human and environmental uses (Seckler 1996).

4 Using the hydronomic zone classification system (Molden and Sakthivadivel 2000) in which a zone is an area where similar strategies can be developed. A natural recapture zone is an area where drainage flows by gravity to a river drainage, and can be reused from the river.

quality is of increasing concern, especially pollution from agro-chemicals.

On the flat floodplains of the Yellow River, loamy soil with high percolation rates dominates LIS. There are two quite distinct zones within LIS — a natural recapture zone upstream of the railway line, and a regulated recapture zone[5] downstream of the line (Figure 2). Land use upstream of the line is dominated by paddy cultivation, with water in excess of crop evapotranspiration (ET) either finding its way to drains or percolating to groundwater. The drains eventually flow to the regulated recapture zone downstream of the railway line. Farmers use drainage canals and groundwater as primary sources of water. As in ZIS, reuse is prevalent, except that LIS relies more on pumping from drains and groundwater, while ZIS uses gravity and surface storage to capture flows.

The role of groundwater is quite different in the two areas. At LIS it is a main source of water below the railway line through pumping. At ZIS it is a significant, but indirect source, with high watertables contributing directly to crop ET. Much of the groundwater at LIS emanates from recharge from the Yellow River and rainfall. Much of the Yellow River recharge is induced by pumping. This underground withdrawal of water apparently goes officially unrecognised in Yellow River Basin water allocations. At ZIS, groundwater levels are influenced by topography and paddy irrigation practices, but it appears that these are not actively managed to control groundwater levels. Fortunately for both areas, salinity is not a major concern. Before large-scale pumping at LIS in the 1960s, watertable rise and waterlogging led to salinity build-up because of little surface or subsurface drainage at the larger system scale. Because of installation of pumps, the drainage at LIS is now adequate. Table 1 give a summary comparison of ZIS and LIS.

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[5] A regulated recapture zone is where drainage water flows to drains or groundwater, and its reuse can be regulated by pumps or other hydraulic structures.
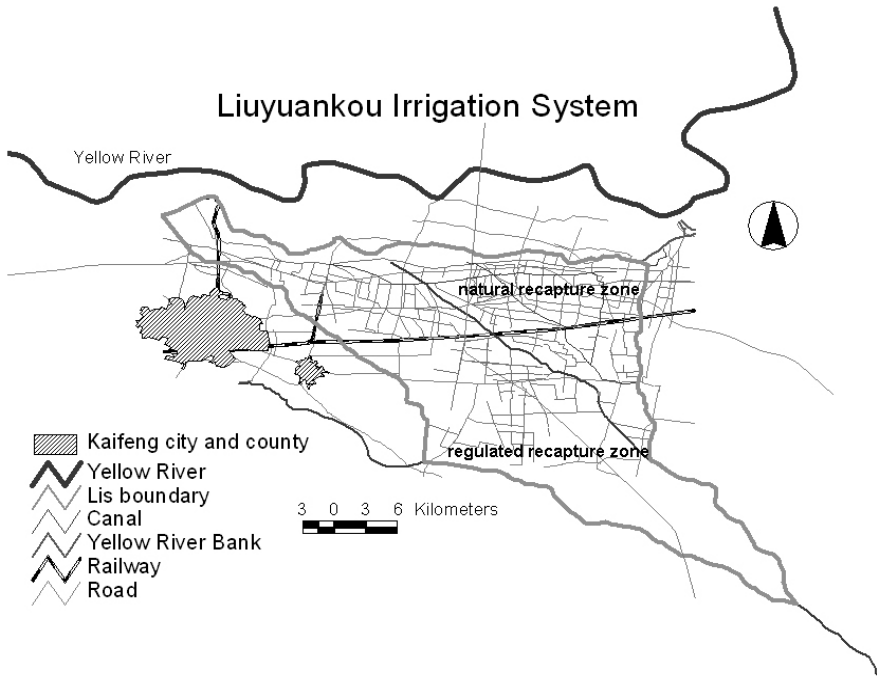

Figure 2. Layout of the Liuyuankou Irrigation System (LIS). The rice area served by canals is north of the railway line, while the diversified cropping system supported by groundwater lies south of the line.

Table 1. Comparing the Zhanghe Irrigation System (ZIS) and the Liuyuankou Irrigation System (LIS): the physical context

ZIS	LIS
Yangtze Basin – 'open' – abundant water	Yellow River Basin – 'closed' – physically water scarce
Natural recapture zone	Regulated recapture zone
Hilly	Flat
Clay loam, low percolation rate	Loam, high percolation rate
Drainage readily (re)captured for reuse – little salinity	Groundwater pumps recharged by water from rain and other sources
Uses surface water storage	Groundwater main storage mechanism
Surface storage prominent	Irrigation and drainage channels used for recharge
Large, medium, small reservoirs	Pumping from groundwater prevalent, especially in downstream areas
Groundwater contributes directly to crops	Groundwater pumped, and contributes directly to crops
Mainly paddy rice in summer, winter wheat and rapeseeds in winter	Less paddy rice and a variety of upland crops in summer, mainly winter wheat in winter

3 Comparing ZIS and LIS: the institutional context

The institutional context has evolved differently in both situations. The multi-tiered organisation of irrigation at ZIS is striking, with several actors — the provincial authority, the Zhanghe Irrigation Administrative Bureau, the canal management authority (three of the four main canals are managed by ZIS, but one is managed by Jingmen City Water Resources Bureau), and village and farmer groups.

The irrigated area of LIS is smaller than that of ZIS, so the LIS is under the direct control of the Kaifeng county and city-level authorities. The irrigation department of LIS is the main service provider to farmers at LIS, delivering bulk supplies of water to village groups upstream of the railway line.

ZIS tends to function as a demand system because of its built-in flexibility to store water in ponds and reservoirs close to the water users (Loeve et al. 2001). While farmers order water through their water user groups or village heads, many of the decisions about when to release water from the ZIS reservoir come from higher up in the canal operation hierarchy. Thus, there is a strong element of supply approach in which the reservoir operators make decisions based on the available storage, rainfall and an overall view of when the crop needs water. Our research tends to show, for example, that the decline in irrigation releases from ZIS over time (Figure 3) has put pressure on farmers to adopt alternate wetting and drying (AWD) irrigation (Cabangon et al. 2004; Moya et. al. 2004), to expand ponds (Mushtaq 2004) and to

recycle water (Loeve et al. 2004a). Furthermore, volumetric pricing at the village or farmer group level, adopted in the late 1980s, has provided a further incentive to save water at the village and farm level (Mao Zhi and Li 1999).

The contrast with LIS is sharp. LIS falls under the local administrative jurisdiction, outside of the command system of the Yellow River Conservancy Committee (YRCC), which controls all the division gates along the river. Though the LIS has a share of the river water, when and how much water can be diverted to the LIS depends on the availability of water in the river and the allocation plan drawn up by YRCC and the Provincial Water Resources Bureau. Despite the fact that the Yellow River Basin is short of water, the institutional structure at LIS, coupled with a rather poorly developed infrastructure, provides no incentive and facilities for rice farmers north of the railway line (Figure 4) to save water. Because of the high watertable and high seepage from irrigation canals, practising AWD in rice cultivation is currently out of the question. Below the railway line, the picture is different, as farmers rely on pumping to grow crops other than rice.

At ZIS, there are multiple needs from the water sector for agriculture, cities and hydropower, and there are growing environmental concern. Water resources, initially developed to serve agricultural purposes, are being shifted to other uses. Allocating enough water to these uses, yet meeting agricultural needs, is a primary objective of system managers. ZIS reservoir managers actively manage the allocation of water to different uses. They receive more income from cities and hydropower than from farmers (Table

3). There is a direct incentive to deliver less to agriculture (in 2000 water fees per sector were CNY 0.0371 for irrigation, 0.068 for cities, and 0.105 for industry). Counteracting this incentive is the role of the Provincial Water Resources Bureau which steps into negotiations about water allocations and try to ensure that enough goes to agriculturalists.

At LIS too there is growing competition for limited supplies. Similarly, it is important to use water to support agriculture, but also to meet other needs. LIS irrigation operators regulate the distribution of their share of Yellow River water only after the river water has passed through the Yellow River diversion gate. In contrast to ZIS, LIS delivers water primarily to farmers. LIS operators are charged a flat, area-based fee, and thus have an incentive to irrigate more area. On the other hand, more releases from the Yellow River would allow the maintenance of a high groundwater table in the rice area through seepage and infiltration. Moreover, the hydraulic infrastructure at LIS affords such poor water control that more precise delivery measures are difficult without an overhaul of the physical system, something which system managers have often pointed out.

4 Water savings and reallocation — why save water?

The numerous participants in both systems have different reasons to save water. One of the findings of the study that was clearly brought home is that the term *water savings* is potentially misleading because of these different perspectives. It is would be better to understand how the flow path of water within the basin or system changes, and evaluate the trade-offs for various stakeholders from the basin to the farmer level, than to say whether or not an intervention saves water. To demonstrate this, we discuss the concept of water savings from various perspectives.

We have already noted that there is a surplus of water in the Yangtze River Basin. Although there has been much debate about the benefits and costs, there are already plans to move water north from the Yangtze River Basin, with the first priority to meet rising non-agricultural demands. At a smaller scale within the study area, the Zhanghe Irrigation Administrative Bureau tends to allocate as much of the reservoir water as possible to higher-value, non-agricultural uses and therefore benefits from prac-

Table 2. Comparing the Zhanghe (ZIS) and Liuyuankou (LIS) irrigation systems: the institutional context

ZIS	LIS
Multi-tiered organisational structure	Under the local government system, not the command system of the Yellow River Conservancy Committee
ZIS reservoir authority serves agriculture, cities, hydropower uses	Irrigation department serves primarily farmers
Financially autonomous reservoir operating authority receives revenue from farm and non-farm sources — financially well-off	Finances collected from farmers are insufficient for irrigation department
Volumetric pricing	Flat rate pricing — lack of incentives to promote farm water savings practice for paddy rice
Good infrastructure, with adequate controlling structures	Inadequate controlling structures
Alternate wetting and drying irrigation promoted	Alternate wetting and drying currently not possible
Farm ponds expanded over time	Heavy groundwater pumping by individuals
The *fee gai shue* (FGS) policy promotes payment directly to irrigation authority	

Table 3. Sources of income (10^4 yuan) for Zhanghe Irrigation System ZIS reservoir operation

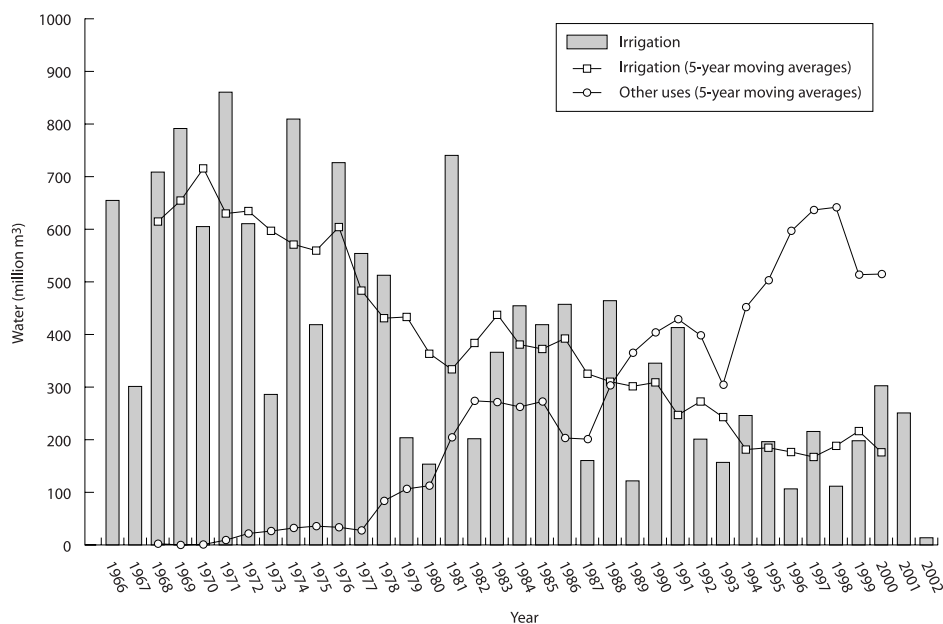|	Appropriation funds from the provincial government	Gross income from agricultural irrigation water supply	Net income from the city and industry water supply	Net income from power generation	Other mixed businesses	Total
Average value (1998~2002)	293	315	246	193	23	1070

Figure 3. Changes in water released to agriculture and other uses over time in the Zhanghe Irrigation System
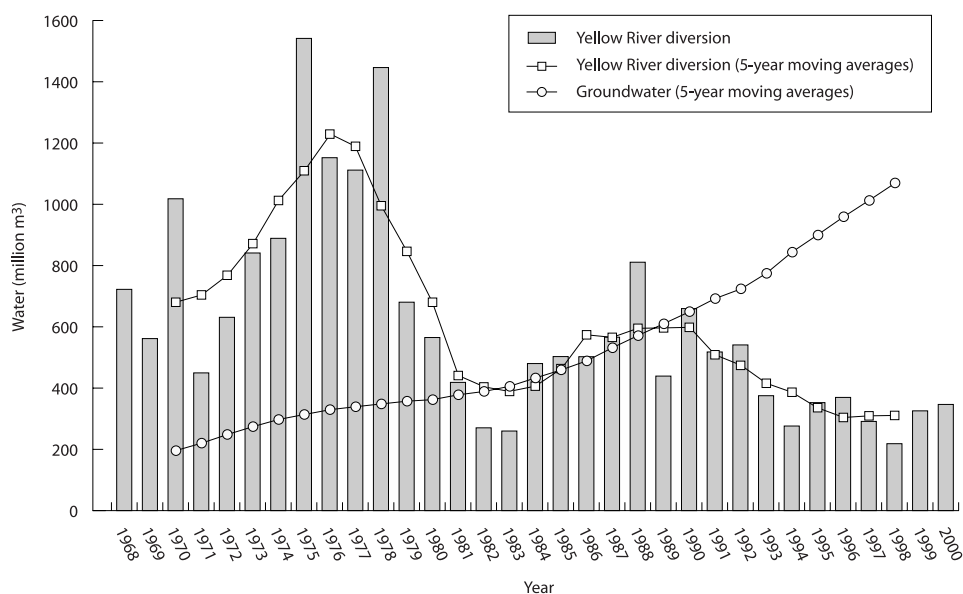

Figure 4. Trends in water use in the Liuyuankou Irrigation System. While Yellow River diversions have fallen, pumping from groundwater has increased.

tices such as AWD, volumetric pricing, canal lining and pond development that enable them to reduce their allocations to agriculture without loss in agricultural production. The canal managers face a different problem. For operating and maintaining the canals, they rely on payments from water users.

During the years 2002 through 2004, a major policy change took place that affected the way water was delivered to farmers from the main reservoir. The policy of *fee gai shue* (FGS) required that farmers get organised to request water from the irri-gation system and make payments directly to the irri-gation authority, when previously their requests went through the village. Water deliveries, and hence income from water fees, were sharply down and canal managers faced a severe budget constraint. In response, farmers relied more on their small storage ponds for water supply, and practices such as AWD helped them to adapt to this policy shift. The farmers have faced both incentives (volumetric pricing) and pressures (reduced deliveries and FGS). As water deliveries to irrigation from ZIS have declined

Table 4. Incentives and pressures to save or reallocate water

Group	Zhanghe Irrigation System	Liuyuankou Irrigation System
Farmer perspective	Farmers acting out of necessity in light of decreasing agricultural water supplies	Understanding the condition of water shortage in the basin and having pressure from water resource managers to 'use' less water
Action	Apply less water through alternate wetting and drying strategy, and increase water fees	Apply less water
Rationale	Response to decreasing supplies	No good reason for farmers, but there is a view that rice is highly water consuming and a long term habit
Incentives	Necessity — get enough water to crops Volumetric pricing to village or farmer groups, cost savings pro-rated to farmers	No great incentive for paddy rice water savings at present
Irrigation operators	No external pressure but incentive to deliver more water within the system	Great external pressure but little internal incentive
Action	Reduce 'losses' from delivery system	Reduce 'losses' from delivery system and deliver less water to rice growers
Rationale	Deliver more water to customers Deliver more water to cities and industries	Deliver more water to more customers
Incentives	More fee collection from farmers, and higher payments from cities and industries.	Expansion of effective irrigation area by canal water
Water resource managers, society	Obtain higher value from water by responding to increasing demand from other uses, yet keeping agriculture healthy	Reduce water for rice to release water for other uses, yet maintain food production.
Action	Reduce withdrawals from reservoir for agriculture	Reduce withdrawals from Yellow River and reduce overall evapotranspiration.
Rationale	Maximising the benefits from the reservoir water	Maximising the benefits from the Yellow River Conservancy Committee allocation, better equity above and below the railway line
Incentives	More value from water	More value from water (increase water productivity) and better equity

(Figure 3) they have adopted AWD, increased the number of ponds and recycled water.

The Yellow River Basin is short of water and there is considerable pressure to reallocate water, especially to the lower reaches of the Basin (Henan and Shandung provinces). Water releases from the Yellow River to LIS have gradually declined and this trend might be expected to continue. Meanwhile, pumping of groundwater for both agricultural and non-agricultural purposes (in nearby Kaifeng City) has increased (Figure 4). Given this situation, the irrigation operators would benefit by reducing seepage from the canal system and delivering less water to the rice producers, and delivering more water downstream of the railway line. A reduction in water to rice could lead to a fall in groundwater levels and a reduction in evaporation losses. Farmers might be encouraged to adopt AWD if convinced that there would be no sacrifice in yield. Reallocation of water could benefit farmers below the railway line.

One of the important and surprising contrasts between ZIS and LIS is the physical context and motivation for saving water. ZIS is located in a physically water-abundant area, while LIS is in a physically scarce area. Yet at ZIS there are more water-saving activities at farm and irrigation-system scale with farmers practising AWD, and managers and extension agents actively promoting means of water savings. At LIS, there is no great incentive for farmers to practice water savings for paddy rice, and the amount of water delivered to fields in relation to ET is high when compared with circumstances in ZIS (Table 5). Again unlike in ZIS, LIS system managers also have no great incentive to be stricter on water deliveries. From a basin perspective, the place that needs to practise water savings (LIS) does not pay attention to it, while the place where scarcity is not an issue (ZIS) is actively practising water savings. What is the reason for this contradiction?

Rice farmers above the railway line at LIS do not seem to have a compelling economic reason to refuse high rates of water delivery to their fields. At ZIS on the other hand, farmers feel compelled to adopt water-saving practices. Yield levels with AWD are about the same as those from traditional practices, and costs are also about the same (Cabangon et al. 2004; Moya et al. 2004). The main reason that farmers practise AWD at ZIS is apparently a response to a declining supply of water to irrigation. The farmer motivation is one of survival — the necessity to cope with falling water supplies. AWD helps farmers to adapt to a condition of lower supply and obtain at least the same output for a lower water input. At LIS, water deliveries remain high. Farmers have no real reason to practise AWD, and in fact do not.

Table 5. On-farm water application for paddy growth season[a] in the Zhanghe (ZIS) and Liuyuankou (LIS) irrigation systems

	ZIS (1999–2000)	LIS (2001–2003)
Irrigation application (mm)	417–470	512–590
Rainfall (mm)	407–310	462–360
Total inflow (mm)	824–780	974–950
Rice evapotranspiration (mm)	613	525
Yield (kg/ha)	7925–6500	7636

[a] The growth season for paddy is from about 20 May to 10 September at ZIS, and from 20 June to 20 October at LIS. The data are from Lu et al. (2003) and Dong et al. (2004)

We can explore the role of pricing in both cases. There is a flat, area-based pricing scheme at LIS, so there is no incentive from rice farmers to reduce deliveries. Downstream of the railway line, farmers pay the electrical costs of pumping, and employ water-saving practices and technologies (for example, they use a flexible pipe called a 'white dragon' to carefully deliver water to fields with minimum seepage). At ZIS, in contrast, volumetric pricing at the village or farmer group level was introduced in the 1980s (Mao Zhi and Li 1999). Cost savings are pro-rated to individual farmers, providing an incentive to adopt water-saving practices. One could argue, however, that reduced deliveries from the reservoir provided the primary incentive for adoption of water-saving practices.

5 Basin and system level outcomes

As already noted, there is pressure for water savings along the Yellow River. Any wasted water in agriculture would readily be used to serve environmental, industrial or urban needs or, for that matter, to better serve agriculture. There is intense societal pressure to save water.

At ZIS, in contrast, there is a need to make sure that various sectors are allocated sufficient water. This process of allocation and re-allocation is done at the sub-basin level by reservoir managers at ZIS. In con-

trast to the Yellow River, along the Yangtze River there is evidently no great pressure to make sure more water flows in the river.

At both systems, an important way to reallocate water is to 'save' water that is perceived to be wasted (down the drain), and reallocate it to other uses. This already takes place at both systems. The depletion fraction measured at the scale of ZIS shows that about 90% of water is depleted by various uses and that there is therefore little remaining scope for additional savings. In fact, of concern is the need to meet downstream commitments for human or environmental needs. These should be considered before trying to recapture further water before it leaves the system boundaries.

Table 6. A summary of incentives to save water among the different stakeholders in the Zhanghe (ZIS) and Liuyuankou (LIS) irrigation systems

	ZIS	LIS
Farmers –		
reduce application	Medium	Low
reduce E or ET	None	None
Irrigation managers –		
reduce delivery to agriculture	High	Low
Basin resource management		
reallocation	High	High
reduce E	Low	High

Reducing evaporation or transpiration fluxes is another way to 'save' water. Evaporation is targeted first, because transpiration is directly related to the marketable yield of crops. At LIS, there are evidently high rates of non-productive evaporation from areas of shallow groundwater. It seems that no attention is being given to this at present. A reduction in this would free-up water that could be reallocated. At ZIS, crop ET is only 36% of total ET in the area. Major shifts in land use could change ET. A reduction in ET from the area would, however, mean more flows reaching the Yangtze River, which is potentially detrimental given the river's propensity to flooding, and not necessarily beneficial from the overall basin perspective. The past strategy has been to limit drainage flows out of the ZIS area, and convert these into more ET.

Table 6 summarises incentives by different actors to change water use. At ZIS, the incentive is one of survival in light of reduced supplies, and for system managers, there is a strong financial incentive. There is little incentive for farmers or system managers to target evaporation losses.

6 The role of secondary storage and rain

Irrigation studies have traditionally considered the role of delivering water from the main sources — reservoirs or canals. An important reason for this is that initial investments are made in dams, reservoirs, diversion structures and canal systems, and their operation is given due importance. In some cases, secondary storage is built within irrigation to help operations. In other cases, the importance of secondary storage such as small dams or reservoirs evolves over time.

At ZIS, there are literally thousands of small and medium reservoirs within the system, some of which are from the original design in the 1950s, and others which have been added by farmers or local authorities. Most farmers receive water from the main irrigation canals originating from ZIS. In addition, many farmers receive water from small reservoirs or ponds, and some farmers from a third surface source — pumping from drainage canals, or simply using gravity-driven drainage flows from upstream. The combined management of these ultimately determines water productivity. As part of the response to declining water releases from the main reservoir to agriculture, farmers have relied increasingly on these alternative sources.

Over time, farmers have increased the number of ponds (Mushtaq 2004). The temporary introduction of FGS (2002–2004) forced farmers to rely much less on the main reservoir at ZIS. Table 7 shows that. even though reservoir releases to agriculture fell sharply during 2002 and 2003, the overall area and yield did not suffer, apart from a slight reduction in average yield in 2002. Farmers were able to rely on rain and farm ponds for their main water supply. The question arises as to the significance of these ponds and their relation to water-saving irrigation practices such as AWD in enabling the reduction of releases from ZIS. It is generally accepted that the ponds, by providing farmers with a source of water on demand, have facilitated the adoption of AWD. Another question is whether agriculture needs any water from the main reservoir if local sources can provide the supply. Modelling by N. Roost (formerly IWMI, unpub-

lished data) shows that in normal years this may be possible, but in dry years, the reservoir provides a life-saving water source of water.

7 Response to reduced supplies

A response at LIS to reduced deliveries from the Yellow River has been to increase pumping from groundwater. It is doubtful whether the overall supply of water to crops has fallen significantly over time, and whether the overall ET has changed. Groundwater, much of which emanates from the Yellow River itself, has simply replaced surface water diversions into the system. Thus, the groundwater plays a very big role in sustaining agricultural practices and productivity at LIS (Table 8).

Management of rain, both at farm and sub-basin scales plays an important role in overall water management at ZIS. At the farm level, again in response to reduced deliveries, farmers capture as much rain as possible by building high bunds and practising AWD. The latter maintains low water levels within the fields and storage volume to capture rain.

The ZIS system configuration is very effective at capturing and using rain at larger scales. Internal catchments in the system provide water to small and medium reservoirs that ultimately serve farmers. Many small ponds capture excess flows resulting from off-field drainage of rain and irrigation water. At larger scales this capture and recapture of run-off and drainage flows ultimately keeps water within the system to meet the needs of various uses.

At LIS, the rain serves as an important source of recharge. At large scales at ZIS, almost all rain is effectively utilised by agriculture, either directly by crops, or indirectly by providing recharge to groundwater, which is then pumped again for agriculture.

8 What is the scope for water savings and water productivity gains?

Looking at sub-basin scale at ZIS and LIS, the *depleted fraction* is already quite high in both systems, and reducing outflow could have adverse consequences for downstream uses. (The *depleted fraction* of gross inflow is the evaporation and transpiration by all uses divided by the rain plus irrigation inflow.) At both systems, the *process fraction* of depleted water is not extremely high. (The *process fraction* of gross inflow is the rice ET divided by rain plus irrigation inflow and indicates the amount of inflow that is depleted by ET rice.) At ZIS, much

Table 7. The introduction of the *fee gai shue* (FGS) policy resulted in less water being released from the Zhanghe Irrigation System (ZIS) reservoir, but the overall area under paddy and yields were not greatly affected, demonstrating the role of secondary storage in overall water management

Year	Water release from the Zhanghe Reservoir (100 million m^3)	Rainfall (mm)	Area irrigated by water from Zhanghe Reservoir ('000 ha)	Planted area with paddy in whole ZIS ('000 ha)	Yield (t/ha)
2002	0.14	568	9.64	105	8.73
2003	0.38	590	47.44	102	7.52
2004	1.35	703	63.00	113	8.76

Note: farmers reported that the paddy yield in 2002 fell about 20~30%, but the yield data available from ZIS records show that the average yield decline was small. Rainfall figures are from Tuanlin Research Station and other data from ZIS records.

Table 8. Responses to reduction in supplies of water to irrigation in the Zhanghe (ZIS) and Liuyuankou (LIS) irrigation systems

ZIS	LIS
Alternate wetting and drying irrigation	More pumps
Increased ponds and secondary storage	Controlled recharge of groundwater through irrigation and drainage systems
Effective use of rain	Rain important to recharge groundwater
More precise delivery	Reduction of outflow to downstream areas
Cropping pattern change (from two to one rice crop; from paddy to upland crops)	Reduction of paddy area

non-process depletion provides water for non-crop vegetation. At LIS, however, there is a large amount of non-productive evaporation and apparently scope for reducing evaporation.

The concept of water productivity incorporates water savings as well as gains in mass or value. If less water is applied or depleted, this is related to savings. The numerator of the water productivity equation increases when more mass or value is achieved. So even if there is little scope for savings, there could be possibilities for gains in value through improving yield or value of output (reducing input costs or changing crops) for the same amount of water, by reallocating irrigation water to higher-value uses within agriculture (higher-value crops) or between sectors, or by reducing negative externalities. Yield levels are already quite high in both systems. But in both systems there already is a reallocation across sectors that increases the benefit per unit of water. The challenge is to manage this reallocation to ensure that agriculture is able to maintain productivity. The biggest productivity gains may be in reducing externalities such as pollution or damage to other users, but we did not study this aspect in great detail.

9 Scale and water resources management

The studies have amply demonstrated the importance of considering scale in agricultural water management. Considering actions at only the field scale and simply extrapolating up to system or basin level is highly likely to lead to misunderstanding. Many other factors come into play when considering water productivity at larger scales (Table 9).
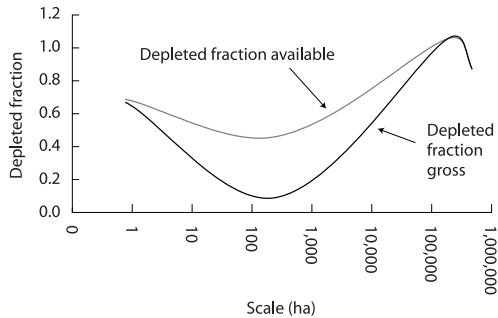
Figure 5. Depleted fraction [ET/(inflow + rain)] estimated at different scales in the Zhanghe Irrigation System (Loeve et al. 2004). The depleted fraction (DF) available adjusts for canal inflow minus outflow across the study domain. Differences in DF across scale are due to farmer practices, influences of other land use, capture of internal run-off and reuse of drainage flows.

At ZIS, our research was aimed at understanding these cross-scale interactions. Figure 5 shows the depleted fraction [ET/(surface and subsurface inflow plus rain)] at different scales. At field scale, the depleted fraction is quite high, because farmers carefully manage limited supplies including rain. But at a meso scale the depleted fraction drops at the study area, because the area contains forests which act as a catchment for downstream areas. Yet at larger scales,

Table 9. Factors that influence water resource use and productivity at various scales in the Zhanghe (ZIS) and Liuyuankou (LIS) irrigation areas

	ZIS	LIS
Micro (field) scale	On-farm water management practices Local influences of groundwater	On-farm water management practices
Meso scale	Run-off and capture in small ponds from other land uses	Reuse of drainage flows originating upstream of railway line Groundwater recharge and reuse
System scale	Influence of non-agricultural uses Water delivery practices Use of water from internal storage Policies – *fee gai shue* (FGS)	Pumping or recharge of drainage water originating from upstream areas
Sub-basin	Influence of multiple uses Consideration of downstream needs	Groundwater interaction with nearby cities Induced recharge from Yellow River Basin

the depleted fraction increases again because of capture and use of run-off, and recapture and reuse of drainage flows. Ultimately, at system level the depleted fraction is quite high, showing that the scope for additional saving in the area is limited.

10 Strategies for water management at ZIS and LIS

Not surprisingly, the strategies employed at ZIS and LIS differ markedly due to the difference in context discussed above. At ZIS the basic approach is to:

- Keep as much water as possible in upstream storage (considering too the need for flood control, which requires low water levels in reservoirs at certain times of the year)
  - Reduce releases to agriculture
  - This promotes the development of internal secondary storage
- Use stored water to control reallocation to different uses
  - Water in the reservoir can be better targeted for city or hydropower use
- Promote gains in water productivity per unit of irrigation supply
  - Because farmers receive an increasingly smaller supply, AWD is a means to adapt. The same yield can be achieved with less water input from the reservoir.
  - Reduce seepage from conveyance structures to allow a higher proportion of canal water to reach farms.

An alternative strategy would be to release ample water from storage, and rely on recycling and reuse of drainage flows. A major disadvantage of this strategy is that it is more difficult, or even impossible, for system managers to control water once it leaves their management domain. For example, if water seeps from canals, farmers are able to reuse it, but system managers cannot capture this water for delivery to other uses.

At LIS, the prevailing strategy is one of conjunctive use. Groundwater provides an important buffer in case Yellow River supplies are further reduced. The results of this strategy have been impressive in terms of low water wastage and high water productivity.

The common view at LIS is that, because rice is a heavy user of water, deliveries to rice farmers should be reduced, or the area under the crop should be reduced. An alternative strategy to the prevailing one is to reduce deliveries to rice, and promote surface water deliveries below the railway line (Figure 2). This could be done by providing better canal control and promoting AWD practices. However, we question whether this will lead to net gains or just a redistribution of water, lessening the need to pump groundwater.

Instead, we propose a shift away from thinking about reducing deliveries to reducing any non-productive evaporation. The strategy is to identify where evaporation is occurring and control water to reduce this. Evaporation occurs from shallow water-tables, especially before and after the rice season. This could be reduced by introducing drainage or reducing deep percolation. Applying AWD may also lower the groundwater depth and therefore reduce the non-beneficial evaporation from fallow land within the rice area. Crop ET of rice is higher than from other potential crops such as maize which has an average ET value of about 420 mm compared with about 525 mm for rice.

There is often confusion and debate about whether we should be thinking in terms of depletion (ET) or deliveries of water. Obviously, both are important, but they carry different levels of importance in different contexts. In the highly stressed Yellow River Basin, which is closed and over-committed, water productivity analysis is better focused on ET. Only by reducing ET will more water be made available, yet maintaining levels of transpiration is important for crop production. In fact, efforts should first be focused on decreasing non-productive evaporation. Manipulating deliveries is a means to achieve this, and reducing deliveries is not the end in itself.

In contrast, in the water-abundant Zhanghe Basin, deliveries are far more important than ET from a water resource perspective (from a service perspective ET is important because it defines crop water demand). More or less ET will not be noticeable in the basin context. On the other hand, water control, keeping water in storage in the upstream areas of the system, and delivering less water, are all means of reallocating water to different uses and of reducing outflows from the system. Thus, considering water productivity in terms of deliveries is entirely appropriate.

11 Rethinking irrigation

In this final section we attempt to identify the general lessons from our research in China. How can the

lessons learned from our two sites be interpreted on a broader scale? The prevailing notion that guides many decisions is that irrigation, especially irrigation for rice, wastes a lot of water. Thus, the focus has been on reducing deliveries and losses from deliveries by lining canals and introducing drip and sprinkler irrigation. The focus is on irrigation supply, and the classical concept of irrigation efficiency (typically estimated at 40% in many Asian systems) doesn't consider return flows and leaves rain out of the analysis. There is also the notion that farmers are the only customers and that irrigation managers are serving farmer needs. It is commonly felt that interventions at the system level (more control infrastructure, better organisation and management) are the main means to change practices. Therefore, if farmers would pay the real cost (full cost) of water, saving water would take place. In light of scarcity and competition, an expanded view is required when in comes to developing a strategy for increasing the productivity of water.

Everyone will agree on the importance of water savings to make most effective use of water. But we have shown that there can be several perspectives (farmer, irrigation manager and society), with different and competing objectives (save water so that more area can be irrigated, save water to save money, save water so that it can be reallocated to cities). Rather than using water savings as an operational term, it would be better to follow paths of water from source, to delivery to a use, to evaporation, run-off and deep percolation flows, then to the fate of these flows including reuse. Changes in management strategies will affect flow paths, incurring costs for some, and producing benefits for others. Decisions should be guided based on these changes in flow paths, and an understanding of who gains, and who bears the cost.

Quite often, farmers rely on *multiple sources* of water including both ground- and surface-water storage, yet much effort by irrigation authorities is placed on managing reservoir and canal water. Rain represents a significant source that is often overlooked. A challenge is managing rain by capture in the field and harnessing run-off generated within irrigation systems as is done in ZIS. Strategies should better take into account that farmer investments in constructing sources and tapping sources, such as we have seen in ponds at ZIS, can mitigate problems of scarcity and affect what happens at a larger scale.

Irrigation must be a responsible user of water in a basin context, as demands for non-irrigation uses of water grow. In spite of calls for integration, irrigation is still dealt with in isolation. In reality, irrigators often have no choice but to adapt to decreasing supplies due to reallocation to other uses, as happened in both case studies here. Not only is it important to understand these cross-sectoral interactions, but also to engage in negotiations across sectors.

An understanding of context and scale considerations will help to identify opportunities and avoid pitfalls. It is vital to consider the system- and basin-level consequences of actions taken at farm and field scale. Similarly, basin actions such as reallocation affect farm actions. The concept of open and closed basins provides an initial insight on context. Strategies appropriate for open basins — managing deliveries for high-value productivity while sustaining agricultural production — may have to shift when basins close due to increased development and competition for water resources. In closed basins, typically found in the semi-arid regions, there appears to be an opportunity for water productivity gains through reduced evaporation. This has not yet been a focus of many water-savings activities. With increasing population and demands on water, basins will become more closed, and there will be a need to shift our thinking to the use (evaporation and transpiration) side of the equation, rather than the supply side.

Especially in closed basins, it is important to recognise that a change in use will affect other uses of water. Strategies to enhance water productivity should first target flow paths where the use of water is generating negative or low values (recognising the values generated by other ecosystems) — for example, evaporation from shallow watertables. If a change is suggested, it is important to evaluate what happens to the water flow paths, then consider the trade-offs, who wins, and who loses. For example, a reduction in drainage flow may affect a downstream user. Is or should the downstream user be compensated?

Following this logic, reducing evaporation in closed basins such as the Yellow River Basin brings an opportunity to free-up water with minimal impact on other uses. This is a much different approach and requires different analysis than approaches that target reducing deliveries (e.g. sprinkler irrigation) or seepage (canal lining). The approach is to identify and quantify non-productive evaporation fluxes, then develop strategies on how to reduce these.

Our studies and experience have clearly demonstrated that there are multiple actors (farmers, irrigation managers, basin managers, broader society) who

influence effective use of water, yet who typically have quite different outlooks and objectives on water use. Policies and strategies for changed water use and management must aim at aligning these objectives and incentives for all actors to obtain wider goals of improved water use.

Acknowledgments

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Evaluating system-level impacts of alternative water-saving options

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Abstract

Improving water-use efficiency is crucial to both Australia and China. In the case of China, development in the last half century has resulted in the irrigated area growing to 53 million ha, which accounts for 40% of the farmland. The total water used for irrigation in China gradually increased from approximately 100 billion m^3 in 1949 to 358 billion m^3 in 1980, since when it has stabilised. However, competition for water from other sectors is increasing. Industrial and municipal water use, for example, have increased rapidly and reduced the proportion used in irrigation from 92% in 1949, to 80% in 1980 and 65% in 1997. This situation demands major improvement in water use-efficiency for irrigated agriculture if current production levels are to be maintained or enhanced.

Irrigated agriculture makes up 70% of Australia's consumptive water use. With the water resources in irrigation areas being close to fully allocated, or even over-allocated in some catchments, there is increased competition for water. It is generally accepted that there will be less water available for irrigated agriculture in future and the only way to provide enough water for that purpose will be to use the available resource more efficiently at both farm and catchment scales.

In both China and Australia, since it is almost impossible to withdraw more water from existing resources, the present irrigation practices and future irrigation developments should focus on improvement of water-use efficiency in all sectors at all scales. However, savings from one part of the system may lead to higher water use in another part of the system and the overall improvement may be negligible. Some measures that may improve the water productivity in agriculture are canal lining, irrigation scheduling, advanced irrigation technologies, improved cropping patterns and conversion to crops with higher economic returns. The key to achieving real and substantial water savings lies in the assessment and hydrologic ranking of water saving options in a whole-of-system context.

This paper describes results of a major water-use efficiency study in the Murrumbidgee Valley, Australia and similar basin-level studies in China. Benefits of a systems approach are summarised through a hydrologic evaluation of water saving interventions at the field, irrigation area and catchments levels for the case studies. Use of a multi-scale, whole-of-system approach can lead to true water savings, improved socioeconomic conditions and future environmental sustainability.

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节水方案选择的系统影响评估

摘要：改善灌溉用水效率对澳大利亚和中国都十分重要。经过过去半个世纪的发展，中国的灌溉面积已达到了5300万 ha，灌溉面积占耕地面积的40％。灌溉用水量从1949年的1000亿立方米逐步增加到1980年的3580亿立方米。之后灌溉用水基本维持稳定，但是其他部门的用水竞争在不断增加。例如，工业和市政用水快速增加，灌溉用水所占比例从1949年的92％分别降低到1980年的80％和1997年的65％。如果要维持或提高现有的生产水平，就需要提高灌溉农业的用水效率。在澳大利亚，灌溉农业用水占到了总用水量的70％。灌溉区域的水资源近乎于全部分配完毕，在某些流域甚至存在超量的水量配置问题，对水的竞争在增加。一般认为，在未来灌溉可用水量会减少，使灌溉获得足够水量的唯一出路是在田间和流域尺度上使可获得的水资源实现高效利用。在中国和澳大利亚，从现有的水源引取更多的水似乎是不可能的事，现有的灌溉实践和未来的灌溉发展应当集中在改善各尺度上所有用水户的用水效率上。但是，在系统的一个部分上节约的水可能会导致系统的另一部分用水增加，忽略了从总体上改善用水效率。改善农业灌溉用水生产效率的措施包括应用渠道衬砌、灌溉制度、先进灌溉技术，改善灌溉模式和种植经济价值高的作物等。实现真实的和较大的节水有赖于在整个系统范围内进行评估和对节水方案进行水文排序。该论文叙述了澳大利亚墨累河流域在灌溉用水效率方面的主要研究成果，以及中国柑近流域的研究成果。通过对田间、灌区和流域节水措施的水文评估，对研究实例的系统方法效益进行了总结。多尺度、整体的系统方法可以实现真实节水、改善社会经济条件和未来的环境可持续性。

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Introduction to a multi-scale hydrologic systems approach

Improving water-use efficiency is crucial for Australia and China. In both countries, since it would be almost impossible to withdraw more water from existing resources, the present irrigation practices and future irrigation developments should focus on improvement of water-use efficiency at both field and catchment scales. The key to achieving real and substantial water savings lies in the assessment and hydrologic ranking of water-saving options in a whole-of-system context.

Figure 1 shows the water cycle in an irrigated catchment at different spatial scales. Key intervention points for improving the sustainability of irrigation systems are shown with numbers in circles. The factors that can be acted on at these intervention points are described below:

1. the volume and regime of water extraction from the river; water rights definition; trading and regulation of use of water rights; improved distribution and control of water delivery to farms

2. the volume and regime of water extraction from groundwater — extraction must be matched by catchment and river recharge; improved delivery to farms

3. the volume and regime of subsurface drainage; improved management to reduce leaching and drainage to groundwater; reduction of salt load to groundwater through soil storage; improved interception of subsurface drainage water and reuse through bio-concentration and extraction; salt management schemes for subsurface drainage and groundwater

4. reduction of water extraction through greater on-farm water-use efficiency

5. improved management of surface water drainage; improved reuse; reduction of contaminants

6. land-use management to control water yield and the amounts of salt and pollutants carried to rivers and groundwater
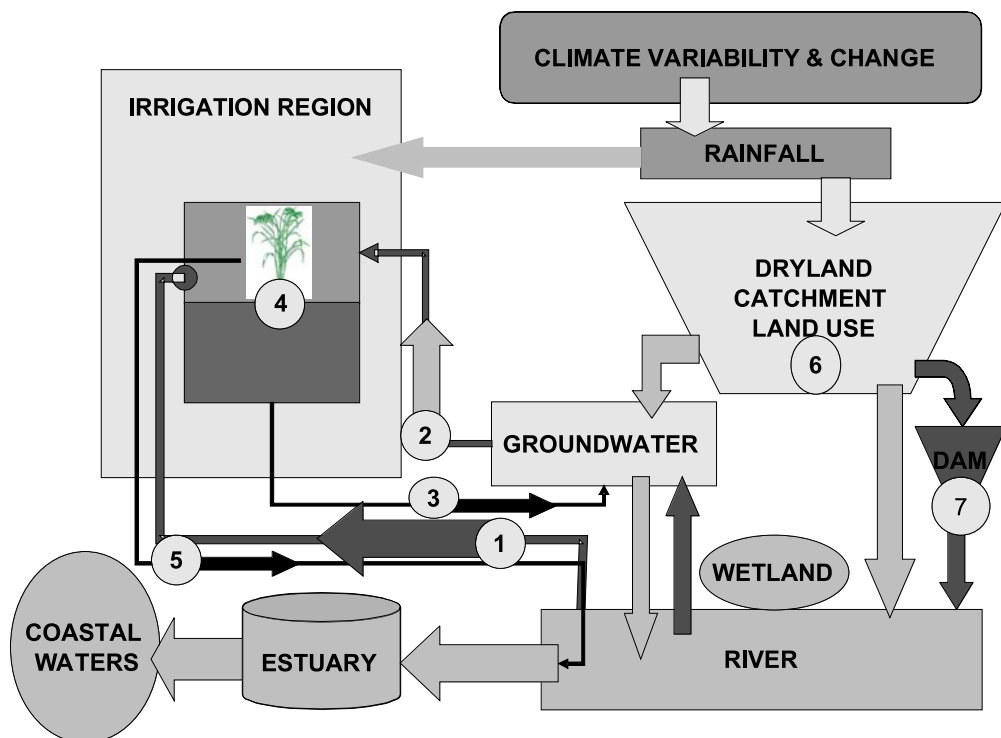

Figure 1. Schematic of an irrigated catchment, showing with key points of intervention for water saving

7. adaptive irrigation management under circumstances of climatic variability and change.

This paper describes results of water-use efficiency studies focusing on intervention points 1–5 in Figure 1, for catchments in Australia and China.

Application of systems approach in Australia

To identify 'true' water-saving options it is important to adopt a multi-scale systems approach for accounting of all surface water and groundwater use and losses and devise interactions at the catchment, irrigation area and farm levels. An example of a systems analysis — for the Murrumbidgee River in Australia — is given in the following sections.

Catchment scale

The Murrumbidgee River (Figure 2) has a catchment area of around 84,000 km^2 and a length of 1600 km from its source in the Snowy Mountains to its junction with the Murray River. The Murrumbidgee (MIA) and Coleambally (CIA) irrigation areas are major irrigation areas situated along the Murrumbidgee Catchment. The geographic boundaries of the Murrumbidgee catchment include the Great Dividing Range in the east, the Lachlan River Valley to the north and the Murray River Valley to the south.

The 100-year flow averages show that the total water resources of the Murrumbidgee catchment are made up of average annual flow downstream of Burrinjuck and Blowering dams of around 2900 GL. From dam walls to Wagga Wagga, there is a net gain of around 1460 GL/yr. Between Wagga Wagga and Darlington Point there is an apparent loss of around 170 GL/yr. From Darlington Point to Hay the river recharges the aquifers of the lower Murrumbidgee system with an apparent loss of around 120 GL/yr. Similarly, between Hay and Balranald there is an apparent loss of around 190 GL/yr. An example of a system's water balance in shown in Figure 2, for the Murrumbidgee catchment in Australia in 1991.

Under the present cropping regime and irrigation practices in the Murrumbidgee catchment, the average true water losses in the system are:
• evaporation from the river ~ 70 GL
• supply and storage losses (seepage and evaporation) in the MIA ~100 GL
• on-farm losses in the MIA ~ 90 GL
• supply losses (seepage and evaporation) in the CIA ~30 GL
• on-farm losses in the CIA ~ 45 GL.

This analysis has shown true losses of greater than 300 GL (Khan et al. 2004b), indicating the potential for real water savings and better environmental management by investments in management and infrastructure.
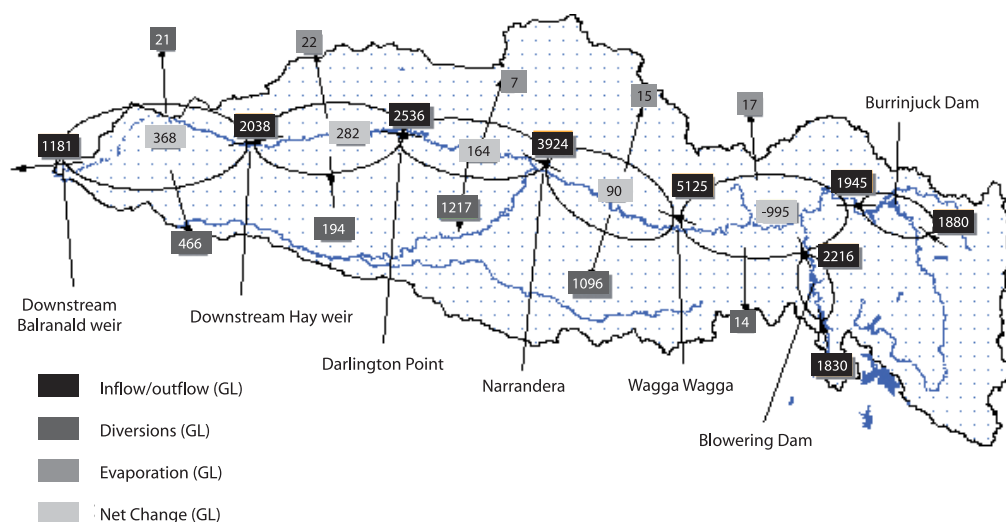

Figure 2. A system's water balance: the Murrumbidgee River, Australia at catchment level 1991. All values are in gigalitres (1 GL = 10^6 litres = 10^6 m^3)

Irrigation area scale

Systems analysis at the irrigation area scale provides indications of water savings at the whole-of-irrigation-area level. Figure 3 gives a system water balance for the Coleambally Irrigation Area (CIA), which spans over 80,000 ha of land. This water balance provides a possible water-use efficiency scenario for the CIA (using 2000–2001 water allocations). The water-use efficiency at various points within the system is expressed in terms of water delivered versus the water supplied and net water use through evapotranspiration and the tonnes of produce/GL. Key water-use efficiency indicators for the CIA show that irrigation efficiency in terms of root-zone storage to the water diverted from the source is 70%. Unless there is an investment in irrigation infrastructure to improve measuring, monitoring and loss reduction, this efficiency indicator will remain low. The overall water-use efficiency of the CIA is 77% due to capillary water use by the crops. Production efficiency of the CIA is 343 tonnes/GL. Further analysis of the whole of the CIA water savings shows (Khan et al. 2004a) that it is possible to increase economic water-use efficiency from $91,000/GL to $97,500/GL, and total water use efficiency from 77% to 84% under the current cropping and irrigation regimes.

Farm scale

The current state of water use and water productivity in the MIA is summarised in Table 1, which provides an overview of the net crop-water requirements (NCWR), current irrigation levels and yields in the MIA. In all cases NCWR are well below the maximum reported irrigation application levels. There are major differences between minimum and maximum crop yields, as well as the overall amount of water consumed and the NCWR. These data clearly illustrate that there is a potential to increase farm profitability through:

- better matching of soils and groundwater conditions with cropping systems
- improving irrigation efficiency by 1–5 ML/ha
- increasing crop yields by 20–50% by removing the management, nutrient and salinity constraints.

The possible water savings can be summarised in the form of steps of increasing on-farm and off-farm
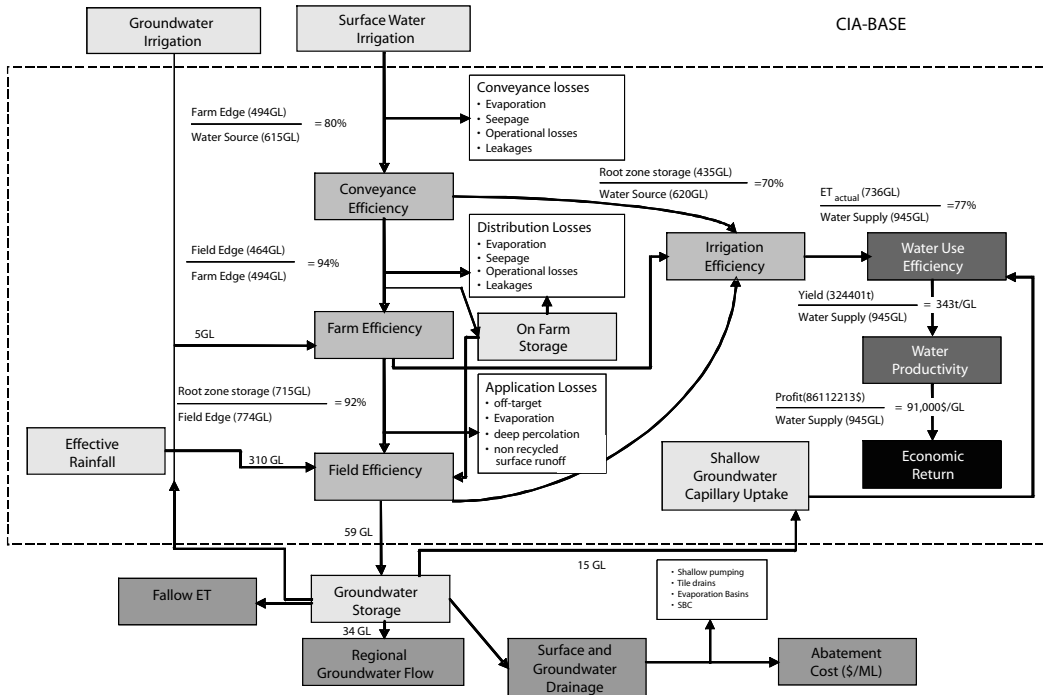

Figure 3. Base case water-use efficiency of the Colleambally Irrigation Area, Australia

water savings and water benefits. It is important to recognise that some steps are prerequisites for the next water-use efficiency level. For example, to realise on-farm water savings it is crucial to implement soil management and groundwater and flow monitoring programs, to ensure irrigation levels are being matched with the crop water requirement, at the same time considering conversion to advanced irrigation technologies. Similarly, to realise off-farm water saving options it is vital to know how much water is being delivered in space and time before piping/lining of channels. It is important to reduce the conveyance difference and narrow the wide gap between the gross diversions from rivers to deliveries to farms by installing state-of-the-art monitoring and delivery systems as a part of the modern irrigation infrastructure.

Considering a range of soil, water and groundwater conditions, Khan et al. (2004b) concluded that on-farm irrigation technology conversions can provide potential water savings ranging from 0.1 to 2.2 ML/ha for different broadacre crops. For example, for citrus crops, they quote savings of 1.0–2.0 ML/ha for changing from

flood to sprinkler irrigation and 2.0–3.0 ML/ha from flood to drip; for vineyards, the savings are 1.0–1.5 ML/ha for the change for flood to sprinkler and up to 4.0 ML/ha from flood to drip irrigation; for vegetables, they quote savings of 0.5–1.0 ML/ha. Modelling simulations show water-saving potential of 7% for maize, 15% for soybean, 17% for wheat, 35% for barley, 17% for sunflower and 38% for faba bean, if on-farm surface irrigation methods can be replaced with pressurised irrigation systems.

Figure 4 summarises the on-farm and off-farm water savings and environmental benefits for the Murrumbidgee Irrigation Area in Australia.

Based on recent work by Khan et al. (2004a), the potential savings for converting from good surface water to pressurised irrigation systems (travelling irrigators or centre pivots or equivalent) are shown in Table 2.

A study of on-farm conveyance losses on nine farms showed that seepage losses vary from 1 to 4% of the total water supplied, which can amount to more than 60 ML/year.
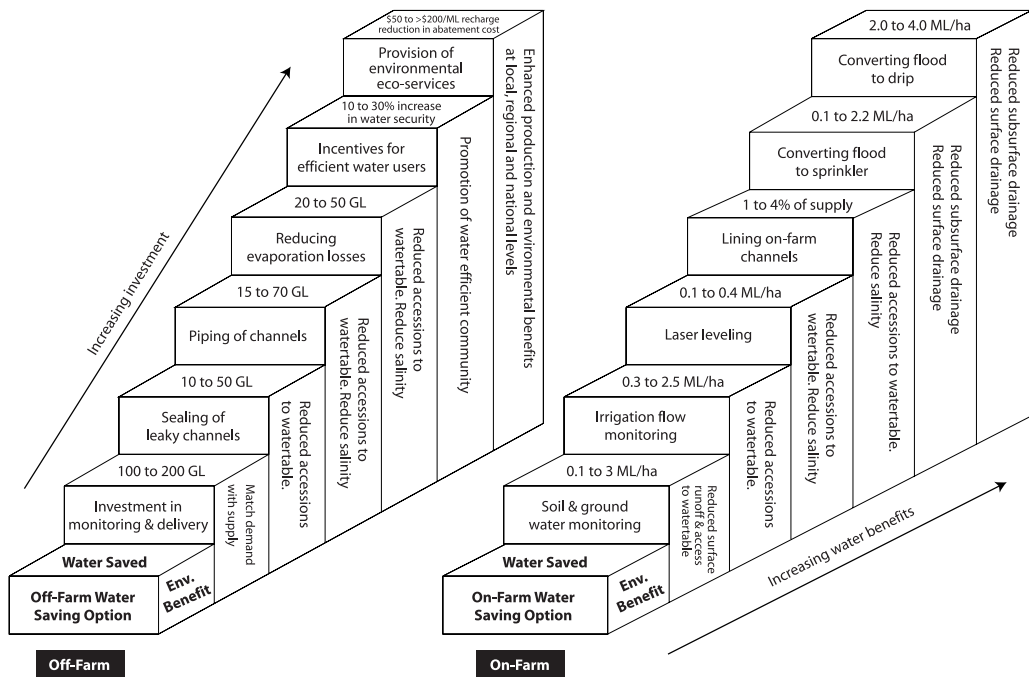

Figure 4. Stairs to possible water savings in an irrigation area

Table 1. Net crop water requirements (NCWR), reported water use and yields in the Murrumbidgee Irrigation Area, Australia. Crop areas are as reported for 2000–2001

Crop	Crop area (ha)	NCWR (ML)	NCWR (ML/ha)	Reported irrigation[a] (ML/ha) Median	Low	High	Reported yield (t/ha) Median	Low	High
Rice	46,120	506,562	11.0	14.0	12.0	16.0	9.5	6.0	12.0
Wheat	39,215	111,835	2.9	2.0	1.0	3.0	5.0	3.0	7.0
Oats	2,896	7,512	2.6	2.0	1.0	3.0	3.5	2.0	6.0
Barley	3,034	8,615	2.8	2.0	1.0	3.0	5.0	2.5	7.0
Maize	2,924	18,813	6.4	8.5	6.0	12.0	9.5	6.0	15.0
Canola	2,685	4,643	1.7	2.5	1.0	4.0	2.5	1.8	3.0
Soybean	2,881	18,383	6.4	8.0	6.0	9.0	2.6	1.5	3.8
Summer pasture	3,929	45,154	11.5	7.5	7.5	8.0			
Winter pasture	24,184	50,403	2.1	5.5	5.5	6.0			
Lucerne (uncut)	2,468	43,291	17.5	10.0	7.0	14.0	7.3	5.0	15.0
Vines	13,635	77,508	5.7	5.0	3.0	7.5	15.0	9.0	25.0
Citrus	8,700	68,861	7.9	7.0	4.5	10.0	38.0	20.0	60.0
Stone fruits	934	9,071	9.7	9.0	7.5	12.0	18.0	15.0	20.0
Winter vegetables[b]	1,500	921	0.6	5.0	4.0	6.0	60.0	50.0	70.0
Summer vegetables[c]	1,500	8,906	5.9	7.0	6.0	10.0	90.0	60.0	120.0
TOTAL	156,605	980,477[d]							

Sources: Beecher (1995), MDBC (1997), MIA&D LWMPWG (1997), Hope and Wright (2003).
[a] Reported irrigations levels are subject to adjustment for measurement error; e.g. 14% is the accepted underestimation factor for Dethridge wheels.
[b] Irrigation requirement and yield is for onions. For salad crops (lettuce) irrigation requirement is 2.0–4.0 and yield is 30.0–40.0.
[c] Irrigation requirement and yield is for tomatoes. For melons, the irrigation requirement is 4.0–7.0 and the yield is 30.0–40.0.
[d] Reported gross diversions for 2000–01 are 1,048,000 ML and on-farm deliveries 857,000 ML.

Table 2. Water use and savings (ML/ha) for selected crops under different irrigation technologies

Crop	Irrigation method								
	Surface			Sprinkler			Water savings		
	High	Low	Average	High	Low	Average	High	Low	Average
Maize	10.6	4.3	8.3	9.2	4.0	7.7	1.4	0.3	0.6
Soybean	6.6	3.6	5.4	5.6	3.2	4.6	1.0	0.4	0.8
Wheat	4.2	0.5	2.4	2.8	0.5	2.0	1.4	0.0	0.4
Barley	4.3	0.7	1.7	2.4	0.7	1.1	1.9	0.0	0.6
Sunflower	7.0	3.5	4.6	4.8	3.1	3.8	2.2	0.4	0.8
Faba beans	4.9	1.5	3.2	3.3	1.4	2.0	1.6	0.1	1.2

Seepage losses measured for over 700 km of channel length in the MIA showed that seepage losses were over 40,000 ML/year and evaporation losses over 12,500 ML/year. The total losses in given channel reaches vary widely and can be 1–30% of the water supplied and 0.2–9% per km.

Application of systems approach in China

Another example of a systems approach is **b**asin-wide **h**olistic **i**ntegrated **w**ater **a**ssessment (BHIWA) for catchment water balance analysis in China. The BHIWA model was developed by the International Commission on Irrigation and Drainage (ICID) in 2003 to specifically address future water scenarios for food and rural development — water for people as well as for the environment — in order to use water resources in a way that achieves sustainable development. The model was designed to be simple, flexible and effective. On the premise that precipitation constitutes the primary resource, management of evapotranspiration to increase the flows in rivers and aquifers is considered as a potential development strategy that could be changed through policy intervention.

The model is able to account for the whole land phase of the hydrologic sector, including the consideration of hydrologic changes due to changes in land use and agricultural activities. The model is capable of depicting surface and groundwater balances separately and allowing depiction of interaction between them, as well as impacts of storage and depletion through withdrawals. Figure 5 is a schematic depiction of the model.

The BHIWA model gives a definition of the water use and yield circumstances for surface water and groundwater, respectively. The model considers the returns as an additional resource added to the natural run-off. In other words, the model considers the 'net consumptive use' rather than withdrawals. Four indicators are selected to depict the water situation in terms of quantity and quality. Indicators 1 and 3 depict the level of withdrawals as a fraction of total available water in the surface and groundwater systems, while indicators 2 and 4 depict the potential hazard to surface- and groundwater quality, respectively.

- Indicator 1   Withdrawals/total run-off for surface water
- Indicator 2   Returns/total run-off for surface water
- Indicator 3   Withdrawals/total recharge for groundwater
- Indicator 4   Returns/total recharge for groundwater

When 0.4 < Indicator 1 < 0.8, it can be concluded that the surface water quantity is highly stressed, while 0.4 < Indicator 3 < 0.8 means groundwater quantity is highly stressed; 0.1 < Indicator 2 < 0.2 suggests that surface water quality is under high threat, while 0.4 < Indicator 4 < 0.8 indicates that groundwater quality is under high threat.

Table 4 gives a comparison of water situation indicators of Chinese river basins in 2000. Based on the BHIWA model, the total inputs to groundwater are the sum of groundwater resources and return flow from well irrigation. The total inputs to surface water (rivers) are the sum of surface water resources and returns. The returns to surface and groundwater were estimated from the surpluses of agriculture, industry and domestic water use (water use minus consumption).
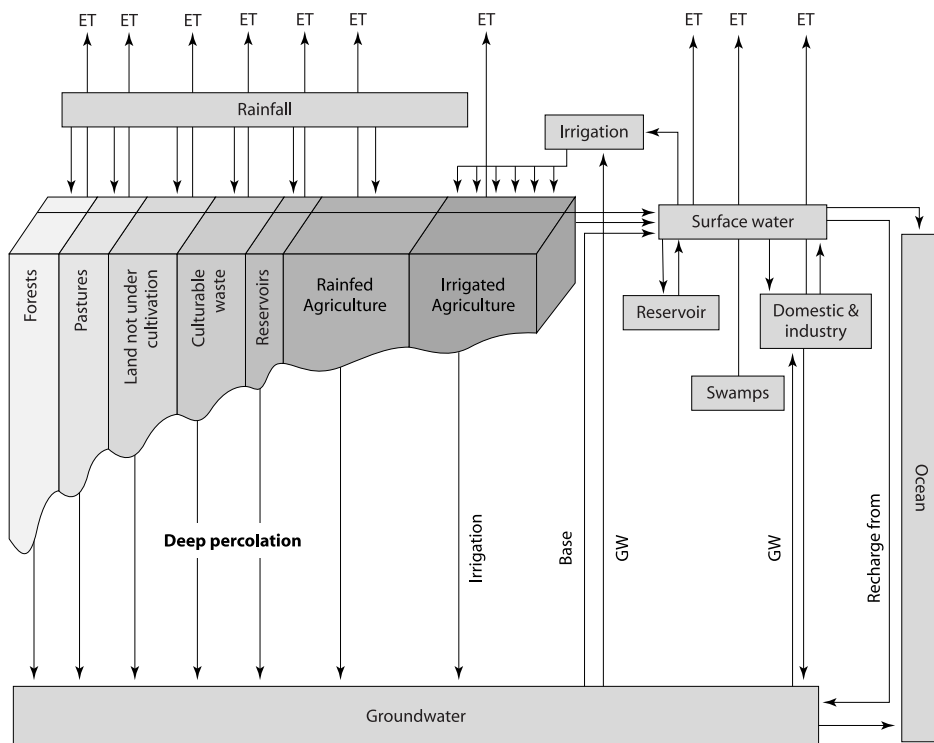
Figure 5. Schematic of the basin-wide holistic integrated water assessment model

Table 4. Water Indicators for Chinese rivers, derived from the basin-wide holistic integrated water assessment model

Class description	Value of indicator	Basin
Very highly stressed through surface withdrawal	Indicator 1 >0.8	None
Highly stressed, through surface withdrawal	0.4 < Indicator 1 < 0.8	Haihe, Huaihe, inland rivers
Moderately stressed, through surface withdrawal	0.2 < Indicator 1 < 0.4	Songliao, Yellow
Low stress, in regard to surface withdrawal	Indicator 1 < 0.2	Yangtze, Pearl, southeast, southwest
Surface water quality under high threat	0.1 < Indicator 2 < 0.2	Haihe, Huaihe
Surface water quality under moderate threat	0.05 < Indicator 2 < 0.1	Songliao, Yellow
Surface water quality under low threat	Indicator 2 < 0.05	Yangtze, Pearl, southeast, southwest, inland
Groundwater very highly stressed through withdrawals	Indicator 3 > 0.8	Haihe
Groundwater highly stressed through withdrawals	0.4 < Indicator 3 < 0.8	Songliao, Huaihe
Groundwater moderately stressed	0.2 < Indicator 3 < 0.4	Yellow
Groundwater low stressed	Indicator 3 < 0.2,	Yangtze, Pearl, southeast, southwest, inland
Groundwater quality under very high threat	Indicator 4 > 0.8	None
Groundwater quality under high threat	0.4 < Indicator 4 < 0.8	Haihe
Groundwater quality under moderate threat	0.2 < Indicator 4 < 0.4	Songliao, Yellow, Huaihe
Groundwater quality under low threat	Indicator 4 < 0.2	Yangtze, Pearl, southeast, southwest, inland

The information in Table 4 shows that system models such as BHIWA can provide a good, system-level indication of surface and groundwater use and the availability of water resources. However, this approach fails to show spatial points of intervention at farm and sub-regional levels. In order to devise actions for improving water-use efficiency at farm, irrigation district and catchment levels it is necessary to carry out a multi-scale water-use efficiency analysis, as described for the Murrumbidgee Catchment in Australia earlier in this paper.

Conclusions

A multi-scale, top-down, systems approach can help assess relative magnitudes of potential water savings. Multi-scale water-balance studies have highlighted the need for accurate measuring and monitoring systems for realising true water savings at the farm, irrigation area and catchment levels. Whereas single-scale, whole-of-system modelling approaches such as BHIWA can provide a good, system-level overview of surface and groundwater use, they fail to show points of intervention at farm and sub-regional level due to the lumped nature of the analysis.

Acknowledgments

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Sustainable irrigation water management in the lower Yellow River Basin: a system dynamics approach

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Abstract

This paper describes a system dynamics study to investigate sustainable water management of irrigation systems in China. Water resources scarcity and irrigation-induced soil salinisation threaten the sustainability of irrigated agriculture in arid and semi-arid areas. The study focused on the Liuyuankou Irrigation System (LIS) in the lower Yellow River Basin. In the lower Yellow River Basin irrigation systems, crops in the upland are usually irrigated with surface water from the river and crops in the lowland are mainly irrigated with pumped groundwater. Seepage from irrigated fields in the upland is an important source of recharge to lowland groundwater. On the other hand, too much seepage and lateral recharge reduces irrigation water-use efficiency and results in shallow groundwater tables that cause secondary soil salinisation. If there is not enough recharge to lowland groundwater, deep groundwater tables increase the cost of groundwater abstraction, and may even result in overdraft conditions. Control of the groundwater table is therefore the key issue in sustainable irrigation management.

In this paper, a conceptual model of the LIS hydrologic system is developed. The dynamic complexity of the system arises because: 1. the components of the system interact with one another; 2. it is governed by feedback; 3. it is non linear and counterintuitive (cause and effect are distant in time and space). The analytical solution of the model is complex. The conceptual model is implemented using the system dynamic tool, Vensim. The model is validated with indirect structure tests. The validated model is used to simulate the responses of the groundwater table. The model provides a comprehensive and general description of the long-term process of groundwater table fluctuations under continuous irrigation practice. Analysis of the model and simulation results reveals under what conditions the groundwater table reaches alarming levels and with what strategies it can be controlled. Strategies for sustainable water-resources development were investigated. The approach presented is also applicable to other similar regions.

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黄河下游可持续灌溉用水管理：一个系统动态方法

摘要：这篇论文叙述了一个评价中国灌溉系统可持续用水管理的系统动态方法。在干旱和半干旱地区缺水和灌溉导致的土壤盐碱化威胁着灌溉农业的可持续发展。这项研究集中在黄河下游的柳园口灌区（LIS）。在黄河下游的灌区，在高地上作物通常引用河水用地表水灌溉而在低地上的作物通常主要通过提取地下水进行灌溉。在高地上灌溉渗漏的水量是低地地下水的重要补给水源。另一方面，太多的渗漏和侧向补给降低了灌溉用水效率，导致地下水埋深浅而引发次生盐碱化问题。如果低地没有足够的补给水源，深的地下水位会使提水成本增加，甚至导致超量开采的情况。因此，对地下水位的控制是可持续灌溉管理的关键问题。在这篇论文里，开发了柳园口灌区的水文系统概念模型。系统的动态复杂性产生原因是：1. 系统组成部分相互影响；2. 反馈信息的控制影响；3.非线性和间接的（原因和结果在时间和空间上相差远）。模型的分析答案复杂。应用系统动态工具，Vensim实施概念模型。用间接的结构检验证实模型的有效性。验证了的模型被用来模拟地下水位的响应。在持续灌溉实践的条件下模型对地下水位长期变化过程提供了综合的和总的描述。模型的分析和模拟结果揭示了在什么条件下地下水位达到警界水位，采取什么对策可以控制地下水位。论文研究了可持续水资源开发对策。介绍的方法也适用于其他相似区域。

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Introduction

The lower Yellow River Basin is one of the important food-production areas of China. In the 1950s, dozens of irrigation systems were developed and they put a new complexion on water-resources utilisation in this area. However, except for the Renmingshengliqu Irrigation System (RIS), in all of these systems diversion of water from the river was stopped in 1962, due to severe secondary salinisation caused by shallow groundwater tables. In the 1970s, according to the experience from RIS, conjunctive use of surface and groundwater was adapted in these irrigation systems. Yang (2002) reported that conjunctive use of surface water and groundwater has four advantages, for it is the way: (a) to increase water-use efficiency, (b) to prevent secondary soil salinisation, (c) to mitigate waterlogging, and (d) to reduce sedimentation.

Surface water from the Yellow River and local groundwater are two key sources of irrigation water in the irrigation systems in this area. Because the river bed is higher than the ground surface beside it, it is easy to divert water from the river. However, due to much seepage loss from the sandy canals to underlying permeable aquifers, surface water is not supplied to whole systems. In the lowlands, crops are generally irrigated with abstracted groundwater. The irrigation tradition and the topography result in differences in the depths of groundwater tables in the systems, which causes recharge from upland to lowland. Seepage from irrigated fields in uplands is an important source of recharge to lowland groundwater. On the other hand, too much seepage and lateral recharge decreases use efficiency of irrigation water and increases groundwater tables, which results in secondary soil salinisation. If there is not enough recharge to lowland groundwater, deep groundwater tables increase the cost of groundwater abstraction, and may even result in overdraft conditions.

Groundwater table control is an important issue of water resources use and sustainable development of these irrigation systems. In this paper, strategies to improve water-use efficiency and maintain proper groundwater tables to prevent salinisation in upland areas and to reduce the cost of groundwater abstraction in the lowlands are investigated by simulating the responses to different irrigation management scenarios.

After a general description of the study area — Liuyuankou Irrigation System (LIS) — the hydrologic conceptual model is developed. Because of the dynamic complexity of the system, the analytical solution of the model is complicated and hard to understand; therefore, the conceptual model is implemented using the system dynamics tool, Vensim (Ventana Systems, Inc. 2003). The model is validated with indirect structure tests. The validated model is used to simulate the responses of groundwater table and salt accumulation under different management scenarios. The model provides a comprehensive and general description of the long-term process of groundwater table fluctuations and soil salt accumulation under continuous irrigation practice. Analysis of the model and simulation results reveals under what conditions groundwater tables reach alarming levels and with what strategies this can be controlled.
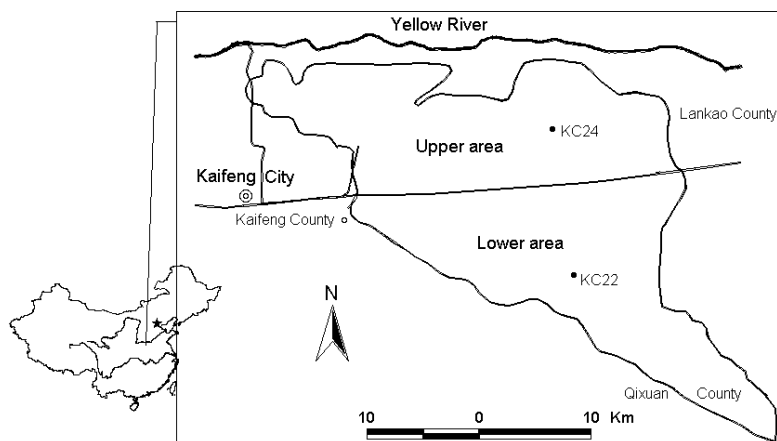

Figure 1. Location of the Liuyuankou Irrigation System in northeastern China

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Finally, strategies for sustainable irrigation water management are investigated.

Description of study area

The LIS is typical of the irrigation systems in the lower Yellow River Basin. The study area is located to the south of the Yellow River in suburban Kaifeng and encompasses an area of about 40,724 ha, including most of Kaifeng County and a part of Kaifeng City and Qixian County (Figure 1).

The LIS has a temperate continental monsoonal climate with cool, dry winters and warm, wet summers. The average annual precipitation for the study area is approximately 627 mm, with ranges from 293.6 mm in 1984 to 991.5 mm in 1997. Most of the annual precipitation occurs during the summer (June–September). The average annual evaporation for the study area is approximately 1316 mm.

Principal sources of recharge to the groundwater basin are rainfall, irrigation (including seepage from canals) and seepage from the Yellow River. The area is divided into northern and southern parts by the Longhai railway line, with a narrow middle area sandwiched between the two. The rainfall in all three parts is approximately the same. There is more recharge (seepage from the Yellow River and canals and irrigation to rice) in the northern part, and the topography of the area gently slopes downwards from northwest to southeast. The groundwater table in the upper part is higher than that in the lower part, which results in lateral flow of groundwater from north to south.

The northern boundary of LIS is the Yellow River, and there is much seepage loss from the river. The southwestern boundary is Huibei Ditch and Huiji River and, in the east, the Quanzhang and Yuni rivers. The ditch and rivers discharge surface flow and soil water, and they can be regarded as symmetrical; therefore southwestern and eastern boundaries can be taken as no-flow boundaries.

Figure 2 shows a general falling trend in groundwater levels during 1996–2002, which was caused by the increasing scarcity of water from the Yellow River. Groundwater level in the upper part (KC 24) fell by only 0.78 m (from 65.33 m in 1996 to 64.47 m in 2002), while in the lower part, groundwater level (KC 22) fell by 2.78 m (from 61.77 m in 1996 to 58.99 m in 2002).

In LIS, when the top of the groundwater table is deeper than 2 m, evapotranspiration is not significant and salinisation rarely occurs (Zhu et al. 2002). The lifts of the most commonly used pumps in LIS are around 10 m. If groundwater depth is less than 10 m, the cost of groundwater abstraction is acceptable and groundwater is available for sustainable use. Therefore, the key of sustainable irrigation water management in LIS is to maintain the groundwater depth between about 2 and 10 m.
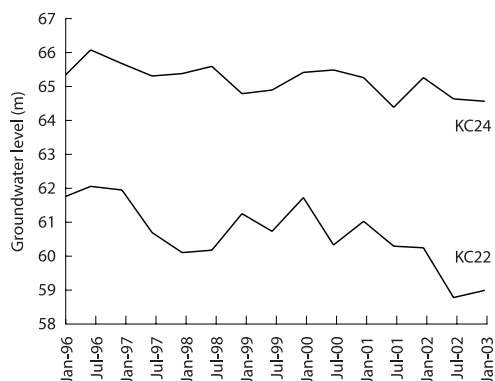

Figure 2. Groundwater table fluctuations in the Liuyuankou Irrigation System in northeastern China

Model description

A dynamic simulation model of surface–groundwater interaction was developed. The system dynamics (SD) approach is an appropriate technique for integrated water resources analysis. The inherent flexibility and transparency is particularly helpful for the development of simulation models for complex water-resource systems with subjective variables and parameters. The flexibility allows the application of hierarchical decomposition in the model development and the transparency raises the possibility of practitioners' involvement in the model development, increasing their confidence in model operation and its outputs (Simonovic 2000). Compared with the conventional simulation or optimisation models, the system dynamics approach is better able to indicate how different changes to basic elements affect the dynamics of the system in the future. It is therefore particularly useful for representing complex systems with strong influences from social or economic elements (Xu et al. 2002). Recent applications of the SD approach in the field of water resources include long-

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term water resource planning and policy analysis (Simonovic and Fahmy 1999), reservoir operation (Ahmad and Simonovic 2000), salinisation on irrigated lands (Saysel and Barlas 2001), and simulation of the hydraulic dynamics in a hydropower plants system (Caballero et al. 2004).

Concept of the model

The LIS is conceptualised into a two-box model to estimate the overall behaviour of the system in time and space. The first box covers the upper part of the LIS, and the second the lower part (Figure 3).

Mathematically, the change of height of the groundwater level in the upper part is described by:

$$\frac{dh_1}{dt} = \frac{(S_{yr} + S_{c1} + P_{f1} + R_1) - (ET_1 + GA_1 + LF)}{A_1 * por_1} \quad (1)$$

where h_1 is the groundwater level in the upper part (m); t is time (years); S_{yr} is seepage from the Yellow River (m^3/year); S_{c1} is seepage from channels in the upper part (m^3/year); P_{f1} is field percolation in the upper part (m^3/year); R_1 is rainfall in the upper part (mm/year); ET_1 is evapotranspiration in the upper part (m^3/year); GA_1 is groundwater abstraction in the upper part (m^3/year); LF is lateral flow from the upper part to the lower part (m^3/year); A_1 is the total area of the upper part (m^2); por_1 is the aquifer porosity of the upper part.

Similarly, we have:

$$\frac{dh_2}{dt} = \frac{(LF + S_{c2} + P_{f2} + R_2) - (ET_2 + GA_2 + LO)}{A_2 \cdot por_2} \quad (2)$$

where h_2 is the groundwater level in the lower part (m); t is time (years); S_{c2} is seepage from channels in the lower part (m^3/year); P_{f2} is field percolation in the lower part (m^3/year); R_2 is rainfall in the lower part (mm/year); ET_2 is evapotranspiration in the lower part (m^3/year); GA_2 is groundwater abstraction in the lower part (m^3/year); LO is lateral outflow from the upper part to the lower part (m^3/year); A_2 is the total area of the upper part (m^2); por_2 is the aquifer porosity of the upper part.

In the above two equations, the evapotranspiration is determined by:

$$ET_i = \begin{cases} A_i \cdot ET_{0i}, h_i \geq h_{si} \\ A_i \cdot ET_{0i} \cdot \dfrac{h_i - h_{ci}}{h_{si} - h_{ci}}, h_{si} \leq h_i \leq h_{si} \\ 0, h_i \leq h_{ci} \end{cases} \quad (i = 1,2) \ (3)$$

where A_i is the irrigated area (m^2); ET_{0i} is the water surface evaporation rate (m/year); h_{ci} is the critical elevation below which evapotranspiration is zero (m); h_{si} is the elevation of ET surface (Chiang and Kinzelbach 1998).

Similarly, S_{yr}, LF and LO are also functions of h_i. Because the interactions between (a) surface and groundwater and (b) upper part and lower part (see
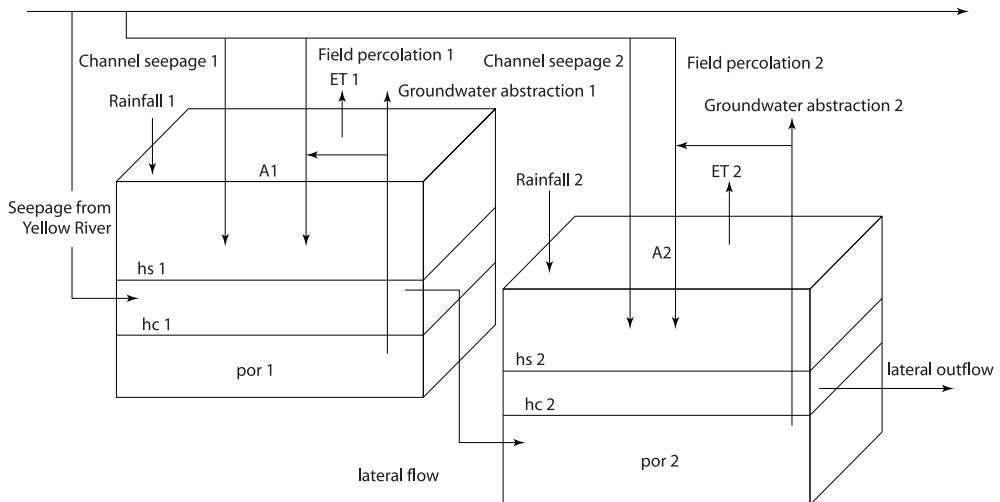

Figure 3. Conceptualisation of the system dynamics model of the Liuyuankou Irrigation System in northeastern China

the section below 'The causal loop diagram'), the analytical solutions of the differential equations (1) and (2) are extremely complicated.

Model structure

The conceptual model is implemented using the system dynamics tool, Vensim (Ventana Systems, Inc. 2003). The model is constructed by building blocks (variables) categorised as stocks, flows and arrows (Figure 4).

The causal loop diagram

Causal loop diagrams are so called because each link has a causal interpretation. In system dynamics modelling, causal loop diagrams represent the major feedback mechanisms, which reinforce (positive feedback loop represent by '+') or counteract (negative feedback loop represented by '−') a given change in a system variable (Sterman 2000). In this model, the feedback loops are all negative. The groundwater storage in the upper part aquifer is controlled by three negative feedback loops representing seepage from the Yellow River, evapotranspiration, and lateral flow from the upper part to the lower part. The first negative feedback loop in Figure 5 represents seepage from the Yellow River: the greater the seepage from the Yellow River, the larger the groundwater storage in the upper part of the aquifer, and then the higher the groundwater level, which in turn reduces the seepage from the Yellow River,

completing the negative or balancing loop. The second negative feedback loop represents evapotranspiration: the larger the evapotranspiration, the less will be the groundwater storage in the upper part of the aquifer, and then the lower the groundwater level, which in turn reduces evapotranspiration, completing the negative or balancing loop. The third negative feedback loop represents lateral flow between the two parts: the larger the lateral flow, the less the groundwater storage in the upper part of the aquifer, and then the lower the groundwater level, which in turn reduces lateral flow, completing the negative or balancing loop. Similarly, the groundwater storage in the lower part of the aquifer is also controlled by three negative feedback loops representing lateral flow, evapotranspiration and lateral outflow.

Validation and analysis of the model

The purpose of a system dynamics study is to evaluate policy alternatives in order to improve system behaviour; therefore, the main criterion of model validity becomes 'structure' validity — the validity of the set of the relations used in the model, as compared with the real processes. Otherwise, the entire study becomes a useless exercise. The validity of the 'behaviour' is also important, but it is different in two ways: first, behaviour validity is meaningful only after the structure validity is established (the 'right behaviour for the right reasons'). Second, a point-by-
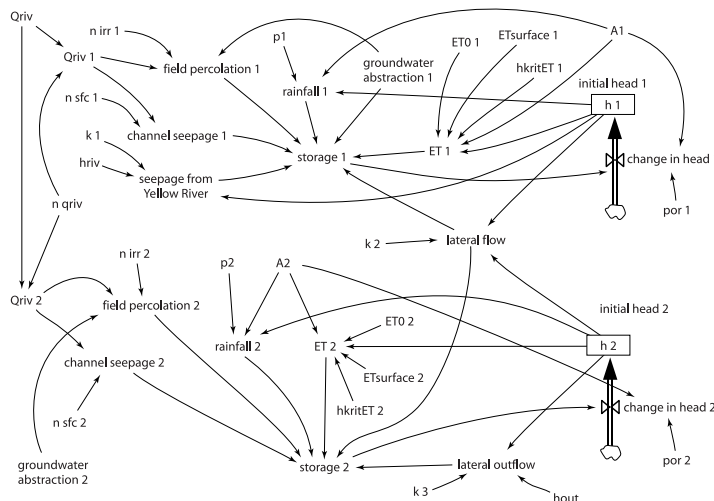

Figure 4. The stocks and flow structure of the dynamic groundwater model for the Liuyuankou Irrigation System in northeastern China

point match between the model behaviour and the real behaviour is not as important as it is in forecasting modelling. What is more important in the system dynamics method is that the model produces the major 'dynamic patterns' of concern (such as exponential growth, collapse, asymptotic growth, S-shaped growth, damping or expanding oscillations etc.). Indirect structure testing is a commonly used way of testing the validity of the model structure, and the two most powerful and practical indirect structure tests are extreme-condition and behaviour sensitivity tests (Barlas 1996; Sterman 2000). In this section, the application of some indirect structure tests to the groundwater model is illustrated.

Figure 6 illustrates the 'extreme' behaviour of the system when no irrigation water is diverted from the Yellow River. It compares the results of the extreme condition run with those of the base run. According to this 'extreme condition' run, because recharge from diverted water decreases, the discharge simultaneously decreases and seepage from the Yellow River increases, groundwater depths in the upper part of the LIS are slightly lower. In the lower part, lateral flow is the main recharge source and, when it changes, the others stay almost the same; the groundwater depth therefore significantly increases. This extreme condition test states that if no water is

diverted from the Yellow River and groundwater abstraction stays the same, the groundwater depth will increase. It also states that the groundwater depth in the lower part of LIS will increase significantly more — a finding consistent with those of Yang (2001).

Figure 7 shows the 'extreme' behaviour of the system when no groundwater water is abstracted in the lower part of the LIS. According to this 'extreme condition' run, when there is no groundwater abstraction in the lower part, groundwater depth fluctuates with the groundwater recharge; the amount of groundwater abstraction in the lower part has little impact on the groundwater depth in the upper part. This is because the impacts can be counteracted (the increase in h_2 causes decrease in lateral flow, which keeps h_1 and then it increases ET_1 and decreases seepage from the Yellow River). This extreme condition test shows the groundwater level recovery under the no-abstraction condition, which is also consistent with the findings of Yang (2001).

In Figure 8, an example of 'behaviour sensitivity' tests is illustrated. The sensitivity of groundwater depth to the percentage of diverted water supplied to the lower part is demonstrated. The model runs correspond to increases in the water supply of 10%, 20% and 30%. It is observed that h_2 is quite sensitive to the
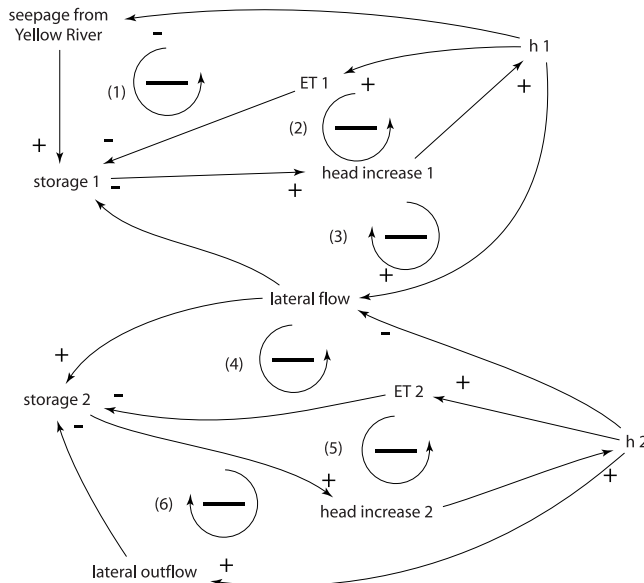

Figure 5. Causal loop diagram for the dynamic groundwater model the Liuyuankou Irrigation System in northeastern China

amount of water supplied to the lower part. This sensitivity shows that the model portrays a logically meaningful relation between groundwater depth and irrigated water.

The indirect structure tests demonstrated that the model formulations have no logical errors or inconsistencies and that the model structure yields meaningful behaviour under extreme parameter values and that the model behaviour exhibits meaningful sensitivity to the parameters.

Results and discussion

The purpose of the presented groundwater model is not to predict what the groundwater levels will be in the future. The purpose is to reveal under what conditions and policies the groundwater heads would continue to rise or fall, if and when they will reach harmful levels, and if and how they can be controlled.

Possible future development options

In recent years, due to decreases in surface water from the Yellow River, some water-saving irrigation techniques have been introduced into the upland rice fields. As a result, the amount of recharge to groundwater has fallen. To achieve sustainable management of irrigation water in LIS, it is important to manage groundwater and surface water and keep the groundwater tables at appropriate levels.

Some of the surface–groundwater management alternatives being proposed to achieve sustainable and economic management of irrigation water in LIS include artificial groundwater recharge to the lower area of LIS using water from the Yellow River (Yang
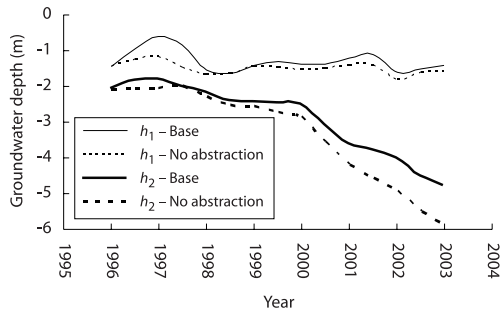

Figure 6. System behaviour in the Liuyuankou Irrigation System, northeastern China, when no irrigation water is diverted from Yellow River: h_1, upper part of LIS; h_2, lower part of LIS
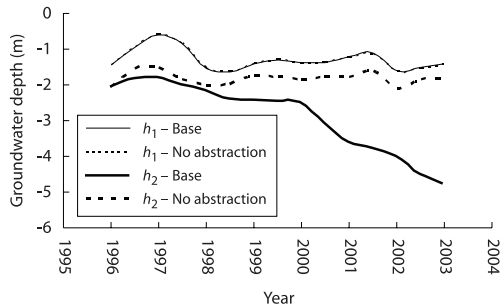

Figure 7. System behaviour in the Liuyuankou Irrigation System in northeastern China when there is no groundwater abstraction in the lower part of the system: h_1, upper part of LIS; h_2, lower part of LIS
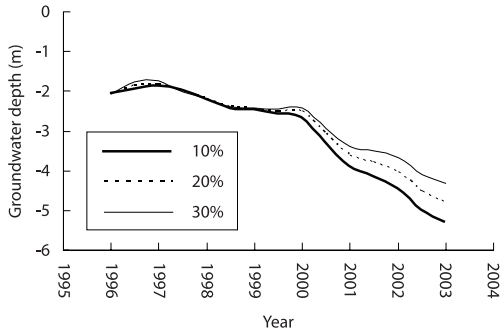

Figure 8. Sensitivity of groundwater level (h_2) to percentage of diverted water supplied to the lower part of the Liuyuankou Irrigation System in northeastern China

Figure 9. Predicted groundwater depths for scenario 1 in application of a dynamic system model to the Liuyuankou Irrigation System in northeastern China

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2001), adopting water-saving techniques for rice in the upper area and allocating surface water to the lower area.

Figure 10. Modelled results for scenario 2 in application of a dynamic system model to the Liuyuankou Irrigation System in northeastern China
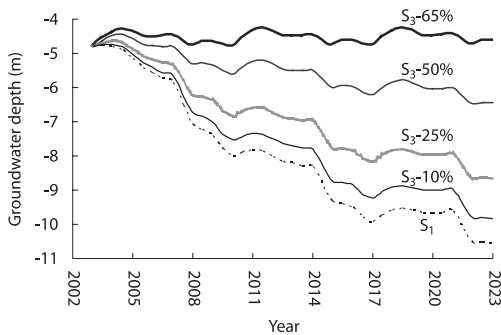

Figure 11. Modelled groundwater depth for scenario 3 in application of a dynamic system to the Liuyuankou Irrigation System in northeastern China

Figure 12. Modelled groundwater depth for scenario 4 in application of a dynamic system model to the Liuyuankou Irrigation System in northeastern China

Considering the existing groundwater conditions (December 2002) as 'initial conditions', a number of future scenarios were evaluated by simulating the response of groundwater levels under changed water management conditions over the next 20 years. All the parameters and assumptions used for the hydrogeological characteristics of the system remain the same. Average recharge rates from rainfall and ET_0 for the period 1996–2002 are used for the 2002–2023 simulation as no significant increase or decrease in the hydro-climatic conditions or flows of the Yellow River is envisaged under predicted climate change scenarios.

The following future scenarios are studied up to the time of 2023:
- scenario 1: No changes in irrigation strategies. The rates of recharge from irrigation and seepage and groundwater abstraction for 1996–2002 are applicable for 2003–2023.
- scenario 2: Water-saving techniques for rice are adopted in the upper area and more surface water is introduced to the lower area (Khan et al. 2004).
- scenario 3: Groundwater abstraction is reduced, either by reducing the cultivated area or improving water-use efficiency.
- scenario 4: Water-saving techniques for rice are adopted in the upper area, surface water is allocated to the lower part and less groundwater is abstracted in the lower area, which is a combination of scenarios 2 and 3.

Results of simulation of future scenarios and discussion

If no changes in irrigation strategies occur in the near future (scenario 1), the groundwater depths in the upper part (h_1) will increase slightly, while in the lower area (h_2), they will continue to increase significantly. After about 15 years, the groundwater depth in the lower area will reach to 10 m, which is the critical value for economic groundwater use (Figure 9).

The simulation results of scenario 2 (Figure 10) show that introducing more water to the lower area is an effective way to stop increasing groundwater depth in the lower area. It is only when more than 70% of the diverted water from Yellow River is conveyed to the lower area ($S_2 - 70\%$), that groundwater depth does not increase significantly.

The simulation results of scenario 3 (Figure 11) show that reducing groundwater abstraction is also an effective way to stop increases in groundwater

depth in the lower area. When the groundwater abstraction is reduced by about 65% ($S_3 - 65\%$), groundwater depth does not increase.

In fact, both scenarios 2 and 3 are not feasible, as it is not possible to reduce water consumption by too much. The simulation results of scenario 4 (Figure 12) show that moderately reducing water consumption at the same time in the two areas is an effective and feasible way to stop the fall in groundwater depth in the lower area of LIS. When 35% of surface water diverted from the Yellow River is conveyed to the lower area and groundwater abstraction is reduced by about 30%, groundwater depth will not increase. In Figure 12, the percentages of surface water conveyed to the lower area and the reductions in groundwater abstraction are, respectively, as follows: $S_4 - 1$: 30%, 15%; $S_4 - 2$: 30%, 30%; $S_4 - 3$: 35%, 15%; $S_4 - 4$: 35%, 30%.

Conclusions

The current challenge of irrigation in LIS is to maintain the groundwater depth when the amount of water available from the Yellow River is falling. Scenario analysis has shown that, if the present irrigation management strategy continues, the groundwater depth in the lower part of LIS will reach 10 m in about 15 years. It is not feasible to stop the increase in groundwater depth in the lower area by reducing water consumption in only one of the areas, whereas moderately reducing water consumption at the same time in the two areas is an effective and feasible way to stop decrease of groundwater head in the lower area.

The system dynamics technique has proved to be an efficient approach for the simulation of a complex water resource system. Its merits include the increased speed of model development, ease of model improvement, and the ability to perform sensitivity analysis. Scenarios other than those investigated in this study can be evaluated using the existing framework. It should be pointed out that some of the current parameters in the model presented were assumed. With more effort on refining the parameters, the model could become a more practical tool for managing irrigation water resources of the lower Yellow River Basin.

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Improving quality and sustainability of irrigation delivery services in China: the case of the Zhanghe Irrigation System

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Abstract

The Zhanghe Irrigation System (ZIS) is located in Hubei Province in central China and receives water from the Zhanghe reservoir to irrigate an area of about 160,000 ha. The ZIS is operated under an arranged demand schedule in which farmers or farmer groups request water deliveries from the supply agency when needed. A two-year research and demonstration project was undertaken in the fourth main canal of ZIS during July 2002–October 2004. Australian and Chinese researchers collaborated to develop an integrated computer and system operation framework to assist in the management of the irrigation system and to estimate the system operation cost, to ensure the sustainability of the scheme in longer term. The process involved a global positioning system based rapid survey of irrigation and drainage structures, implementation of the computer model **i**rrigation **m**ain **s**ystem **op**eration (IMSOP) to simulate the operation, monitoring existing operation, retrospective analysis of the system and water order modelling. The comparison of IMSOP model-simulated demands with monitoring data showed large deviations and consistent undersupply. An additional software utility, Order Manager©, was developed to schedule the water orders. Also developed was generic geographic information system-based asset management software, Asset Manager©, which can be used to manage infrastructure in any irrigation scheme. Asset Manager was used to analyse the long-term investment provisions, and full and partial renewals costs were estimated as 235 Yuan/ha and 140 Yuan/ha at 3% inflation and 5% interest rates. The analysis of the financial performance shows that current pricing of the irrigation service is well below the level needed to ensure sustainability of the infrastructure and water service. This research has provided a useful and practical methodology to diagnose deficiencies in the irrigation system infrastructure and its operation, and to establish the basis of a management system to provide defined levels of service to users. The results of the project are both useful and applicable to millions of hectares of irrigated areas in China.

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改善中国灌溉配水服务的质量和可持续性：漳河灌区实例

摘要：漳河灌区（ZIS）在华中湖北省，它从漳河取水灌溉面积为160,000 ha。漳河灌区按照安排的需求计划进行运行，在需要水的时候农民或农民小组从供水单位申请配水。从2002年7月至2004年10月在漳河灌区的第4条干渠开展了为期2年的研究和示范工程。澳大利亚和中国研究人员合作并发了集成的计算机模型和系统运行框架，以辅助灌溉系统的管理、估算系统运行成本、确保灌区长期的可持续性。整个过程包括了一个对灌排建筑物进行快速测量的全球定位系统，灌溉主系统运行（IMSOP）计算机模型执行程序，用来模拟运行、监测当前运行情况，分析系统过去的运行情况和模拟用水次序。IMSOP模型模拟需求和监测到的数据差异很大，均为供给不足。还对Order Manager©软件进行开发以确定供水次序。还基于Asset Manager©软件开发了基因地理信息系统，这个系统可以用来管理如何灌溉工程的基础设施。Asset Manager 软件被用于分析长期的投资供给，在3%通货膨胀率和5%利息情况下，全部和部分更新成本估计为235元/ha和140元/ha。财务运行分析表明现行的灌溉服务价格远远低于确保使设施和供水服务可持续运行需求。这项研究为诊断灌溉系统设施短缺程度和灌溉设施的运行情况提供了一个有用且适用的方法，建立了一个为用户提供不同水平服务的管理系统平台。项目成果是有用的，且适用于中国灌溉面积上千万公顷灌区应用。

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Introduction

China is one of the largest irrigation countries in the world and irrigation plays a pivotal role in the ability of the country to meet its future food demand. Due to its large population, China has one of the lowest availabilities of land per capita worldwide — 0.1 ha. Most of the irrigated agriculture area in China is supplied by either large- (>30,000 ha) or medium-scale irrigation districts (670–30,000 ha). Competition for water between agriculture and other uses, including urban and industrial, has become severe in large parts of China. In several regions, water has been identified as the most critical constraint to the future sustainability of economic development, especially on the North China Plain. Increasing competition for water between different users across China will reduce the amount of water available for irrigation. Growing water scarcity and the misuse and mismanagement of available resources are the major threats to the sustainable development of the various user sectors (Hamdy et al. 2003). It is therefore an imperative to strive for better management and utilisation of water to meet the increasing competition for this resource.

The ability to meet the aforementioned challenge will depend largely on the performance of irrigation systems (Small and Svendsen 1992). In order to improve the performance of medium- to large-scale surface irrigation systems, irrigation agencies have traditionally sought to upgrade infrastructure through rehabilitation and modernisation programs, and have paid little attention to improve operational management. In the last decade, irrigation researchers have developed and applied computer tools to plan, schedule and monitor the operation of irrigation systems to improve their performance. Simple canal operation models are useful in generating irrigation demand based on evapotranspiration estimates and a realistic description of the delivery system and its characteristics (Turral et al. 2002).

The existing infrastructure at Zhanghe and other irrigation districts in China shows severe signs of decay as a result of age and deficient maintenance practices. The lack of sustainability of the irrigation infrastructure due to the inability to invest in sufficient expenditure in operation and maintenance is of great concern. At present, there are no provisions for linking the cost of operating the irrigation and drainage infrastructure to the actual price charged for those services. This, coupled with the inability of

government to subsidise these services at an appropriate level, places severe constraints in the ability of irrigation management companies to sustain their operation.

A two-year research and demonstration project was undertaken in the fourth main canal of Zhanghe Irrigation Scheme (ZIS) between July 2002 and October 2004. In the project, Australian and Chinese researchers collaborated to investigate and improve the operational performance of the system. This paper is intended to demonstrate the process followed in assessing operational performance of the system and the development of a service costing for the sustainability of the system in the long term.

The Zhanghe System

The Zhanghe Reservoir is built on the Zhanghe River and is a multi-purpose reservoir designed for irrigation, flood control, water supply, hydro-power and industrial use (Figure 1). The climate of the region is typically continental, with a temperature varying from a minimum of $-19°C$ in January to a maximum near $41°C$ in July. The annual frost-free period ranges from 246 to 270 days on average. Rainfall is characterised by a typical subtropical monsoonal regime with an annual precipitation of 970 mm, and large and between-year variability ranging from 610 mm to 1327 mm. Most of the precipitation (82%) falls between April and October, coinciding with the rice-growing season.

The water distribution system in ZIS consists of six main canals (Figure 1):
1. general main canal
2. west main canal
3. first main canal
4. second main canal
5. third main canal
6. fourth main canal.

In addition to the main distribution system, the system includes an extensive network of 13,984 branch canals with over 15,000 structures. The west and first main canal operate under the Dang Yang Water Resources Bureau. The third main canal is managed by Jingmen City Water Resources Bureau. The Zhanghe Irrigation Administration Bureau (ZIAB) controls the general, second and fourth main canals.

This project was designed as a research and demonstration project centred on the fourth main canal of the ZIS (Figure 2). The total length of the fourth main canal is 18.75 km, of which 7.4 km is lined and the

rest is earthen. Generally, the fourth main canal receives water 3–4 times a year and the duration of each irrigation varies between 5 and 15 days. Four management stations operate under the fourth main canal: Longquan, Anzhankou, Wenjia-Xiang and Yanchi.

The fourth main canal bifurcates into two canals: the east branch canal and the north main canal. The east branch canal is 25 km long. The east branch canal operates under two management stations: Wenjia-Xiang and Anzhankou. The east branch canal also supplies water to two townships: Heji and Lengshui. The main grain crops grown in the district are rice and winter wheat. Paddy cultivation accounts for about 80% of the total area, of which about 85%

is planted to summer rice (May–September). The remaining area is planted with a short duration variety of rice later in the season. The main upland crops are beans, sesame and sweet potatoes.

Agricultural water use

The ZIAB is responsible for long-term allocation of water in the system. The annual allocation plan is developed at the start of each irrigation season, based on the surveyed irrigated area, water in storage and inflow forecasts. Agriculture has the first priority for water use. Figure 3 shows the quantity of water released to different sectors from 1993 to 2003. It is clear that there has been a decline in agricultural
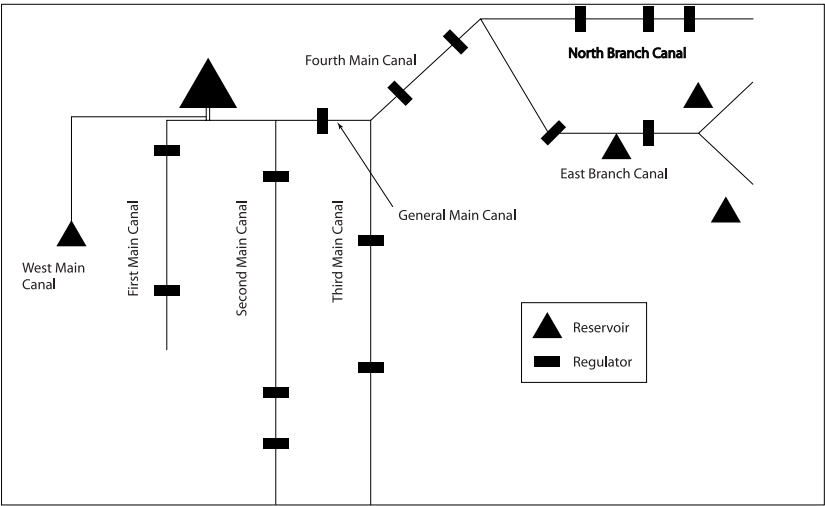

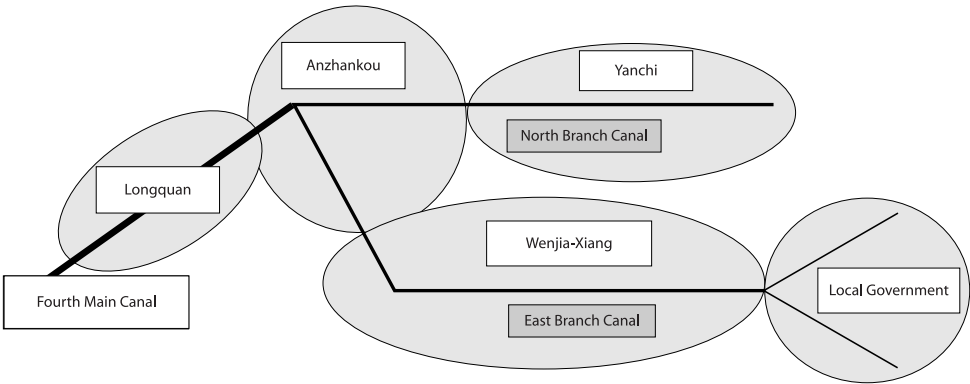**Figure 1.** Schematic of the Zhanghe Irrigation System, central China

Figure 2. The project area in the Zhanghe Irrigation System, central China

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water use in recent years, and that the ZIAB has allocated this freed-up to power generation. After generating power the water is diverted to the river to provide for dilution of pollutants but is not available for irrigation diversion.

Agricultural water use from all sources was estimated at 430 million m^3 in 2001 (Figure 4). Water used for irrigation in the ZIS (reservoir release) for agriculture has declined to 14 million m^3 in 2002 from an average value of 198 million m^3 over the period 1994–2001. The decline in agricultural water use is mainly due to a sharp reduction in ordering by farmers as a result of recent changes in water-pricing policy and institutional arrangements. Notably, no water was supplied to the fourth main canal during 2002.
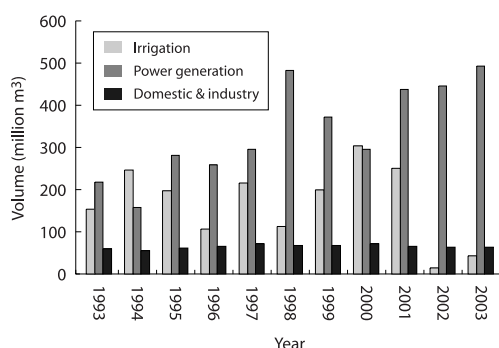

Figure 3. Water releases from the Zhanghe Irrigation System, central China to different sectors
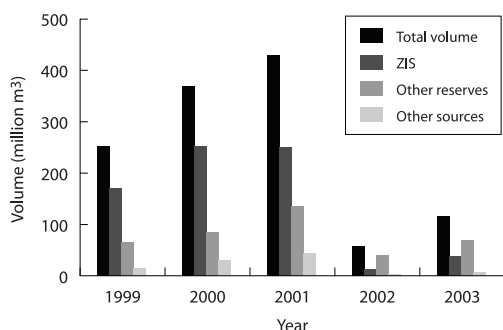

Figure 4. Agricultural water use in the Zhanghe Irrigation System, central China

Operational procedure

Annual operation planning

The ZIS is operated under an arranged demand schedule in which farmers and farmer groups request water deliveries from the supply agency when needed. Farmers' decisions to order water are often influenced by a number of factors, including the actual crop water demand, expected rainfall, the price of water and farmers' perceptions of the system's reliability. Before the start of the irrigation season, water users must submit their water demand and cropping pattern to their respective water management stations (WMSs). Based on this information and the historical water use by farmers, the ZIAB formulates an aggregated annual plan based on the demand and forecast inflow into the reservoir. Once the plan is finalised, the ZIAB signs a contract with the fourth main canal offices (FMCOs) which, in turn, signs a contract with the WMSs. The WMSs will then sign a contract with the farmers or farmer groups before the start of the season. Water users are entitled to the quantity specified in the contract at a basic rate subject to water availability and actual rainfall. If the water use exceeds the specified quantity, farmers are charged at a higher rate.

Day-to-day operation

The day-to-day operation involves the water management stations collating all the farmers' orders which they forward to the main canal offices. During the irrigation season, farmers must place their water orders with the WMSs at least 3 days in advance. If farmers want to change the discharge or to cancel the order, they must apply to the WMS at least 24 hours in advance of the order's delivery. As it takes about 2–3 days of travel time for water to reach the end of the system, once the water is released, farmers must pay the charge for the volume ordered even if it rains and the water is not used. In years with average demand, farmers typically order water three times a year for soaking and land preparation (10–25 May), irrigation (10–20 July), and grain formation stage (mid August). Farmers pay for 30–50% of the water fee on the day of ordering and must settle the remaining amount soon after the irrigation has finished.

Institutional arrangements

The administrative system in China consists of a hierarchy of water resource bureaus, functioning at the township, county, prefecture and provincial levels (Figure 5). The Ministry of Water Resources is in overall charge of the water resources of the entire country. At the top of the irrigation management structure is the irrigation district (irrigation administration bureau) which functions under the provincial adminis-

tration bureau and is charged with managing the entire irrigation system. Below is the main canal office which is responsible for the operation of the main and secondary canals. Water management stations are the subunits of the main canal office and they operate and manage the key water control structures along the canal, with responsibility for the maintenance of branch canals and the collection of water fees.
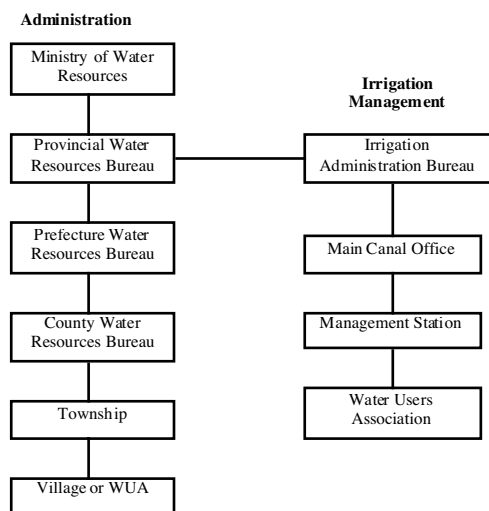
Administration

Ministry of Water Resources

Irrigation Management

Provincial Water Resources Bureau — Irrigation Administration Bureau

Prefecture Water Resources Bureau

Main Canal Office

County Water Resources Bureau

Management Station

Township

Water Users Association

Village or WUA

Figure 5. The organisation of irrigation management in Hubei Province, China

Water pricing system

The Chinese Government introduced wide-ranging reforms in water pricing in the early 1980s, including the volumetric pricing of irrigation water. This policy has had a major impact on the water consumption in some irrigation areas, and has been the main driver in the adoption by farmers of water-saving irrigation practices. Before 2002, a two-tier system of payment for irrigation water was applied in the fourth main canal: a basic charge (30 Yuan/ha of paddy) and a volumetric water fee (0.04235 Yuan/m^3). Generally, farmers used to pay this charge to the village (township) administration which, in turn, forwarded this revenue to the water management stations. The farmers who were pumping water for irrigation had to pay the additional operational cost of pumping. In actual practice, the water management stations received only a fraction of the volumetric water fee paid by farmers after the township administration collected its taxes.

The Chinese Government implemented a new policy called *Fee Gai Shue* in 2002 in which the water fee was separated from other taxes. Under the new policy, farmers are charged on a volumetric basis. The water management stations are responsible for collecting the water fee, which is levied at approximately 0.050 Yuan/m^3. Under this pricing policy the area (rice) based water fee is no longer applied. The policy had an immediate effect on farmers, who responded very quickly by reducing water demand. As a result, the area irrigated fell sharply in 2003 when no irrigation water was demanded by several of the main canals.

The policy was revised in 2004 to reverse the drastic reduction in cultivation. Under the revised policy, farmers are again charged on a two-tier basis: (a) an area-based payment and (b) a volumetric water fee. Both water fees are collected by the water management stations, which then forward the receipts to the main canal office. Under the revised policy, farmers pay an area-based water fee of 75 Yuan/ha and a volumetric water fee of 0.033 Yuan/m^3.

Operational modelling

Modelling of system operation planning

The main function of the irrigation system is to deliver water to satisfy well-defined service provision objectives defined in terms of flexibility, reliability and adequacy. Chinese systems often fall short in one or more of these attributes, depending on the location-specific conditions of the system.

Computer modelling provides the capability to describe irrigation system networks and their operation and test system responses to alternative operational procedures and rules. As part of this project, the **i**rrigation **m**ain **s**ystem **op**eration (IMSOP) model was further developed and adapted to simulate a variety of system configurations and provided with the necessary adaptive capacity to incorporate the more salient features of the irrigation systems.

IMSOP is a steady-state hydraulic model that simulates the operation of the main and secondary canals in an irrigation system (Turral et al. 2002; George et al. 2004). The model calculates the reference crop evapotranspiration using weather station or pan evaporation data, whichever is available. It then calculates steady, uniform flow in the channels on the basis of accumulated offtake demands and transmission losses. The model is based on a graphical user

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interface (GUI) built on Visual Basic 6. A Chinese version of the software has been developed as part of this project.

The model requires the description of the irrigation system in the form of a network diagram, which incorporates all reaches of the main canal and usually some secondary canals, all hydraulic structures on those canals, and all offtakes to secondary- or tertiary-level farm units. All other inflow and outflow points, reservoirs and pumping stations are described as nodes in the network diagram.

The IMSOP model can be used in three ways:

- assessment of historical performance of the irrigation system, comparing simulated performance with monitoring data
- simulation and analysis of alternative operational regimes to enhance system performance
- near real-time operation of the system.

Scheduling water orders

An additional software utility, Order Manager©, to assist the Branch Canal Office in scheduling the delivery of water orders was developed. The utility accommodates the requirements of systems such as Zhanghe that are operated on request. The software is designed to aggregate and route the water orders so as to determine the discharge that is required at the head regulator at different times during the day. The model can also calculate the water charge based on the volume ordered.

The database management system was developed using Microsoft Access™ which allows the operator to enter the water orders into the database using the GUI. The users can also update the water order data or can delete orders if cancelled by farmers. The management office makes use of this utility to aggregate the water order each day and advise the fourth main canal office to release the volume demanded, schedule the delivery to different offtakes and calculate the discharge required at the head regulator at different times (Figure 6). The results can be displayed either as graphs or in reports generated using Microsoft Excel™.

Supply–demand analysis

East branch canal

The performance of the east branch canal system during the 1999–2004 cropping seasons was investigated using the IMSOP model (Figure 7). The water demands simulated by IMSOP were compared with the volumes supplied over this period. This showed that the seasonal demand exceeded the canal supply every year. In some years the canal supply was only 50% of demand. The rest of the crop water demand was met from local water sources (off-line reservoirs and ponds) which are beyond the control of the ZIAB. Supply from these sources was not quantified in the project.

Supply:demand ratios (actual supply versus IMSOP-calculated demand) in different service areas in the east branch canal are compared in Table 1.
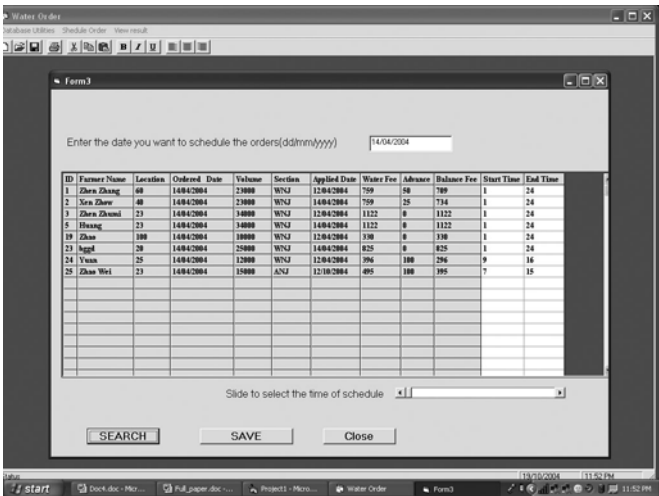

Figure 6. Example of an ordering schedule to minimise canal flow fluctuations

During the 2004 irrigation season, the seasonal demand exceeded supply in all the service areas. The average supply:demand ratio for the entire area shows that 23% of the total irrigation demand is supplied from the Zhanghe reservoir. An unknown amount is supplied in addition by local ponds and reservoirs.
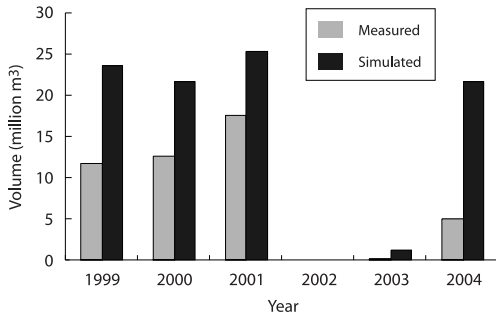

Figure 7. Comparison of water actually supplied and IMSOP-simulated irrigation demand in the east branch canal of the Zhanghe Irrigation System, central China

Table 1. Supply:demand (IMSOP) ratio and its variation in different service areas of the east branch canal, Zhanghe Irrigation System, central China

Service area	2003	2004
Whole system	0.18	0.23
Wenjiaxiang and Anzhankou	0.28	0.26
Heji	No irrigation	0.22
Lengshui	0.08	0.19

During the 2003 season, 18% of the water demand was supplied by the east branch canal. Farmers ordered water only once in the whole season and met the rest of their requirements from the local water sources. Rainfall during the 2003 and 2004 seasons was well distributed, which may have also affected the pattern of demand. A survey of farmers in the third main canal concluded that there is, on average, one pond for every 3.0 ha of rice to supplement the irrigation, yielding an average pond capacity 833 m^3/ha. These ponds are refilled during rainfall events throughout the season. The actual catchment areas and hydrology of these ponds were not analysed in this study.

Main canal system

In order to understand the shortcomings of the existing operation, the seasonal irrigation demand of the ZIS main system was estimated using IMSOP for the water years 1999, 2000, 2001 and 2002, and compared with monitoring data. A comparison of supply and demand for the different parts of the canal system during irrigation season of 1999 is shown in Figure 8. The supply:demand ratio was found to vary from 11% to 55% in 1999 (Table 2), indicating that only part of the irrigation demand is supplied from the Zhanghe main reservoir. During 2002, only 13% of the overall demand was supplied from the Zhanghe reservoir, while in other years the reservoir met up to 50% of the demand.
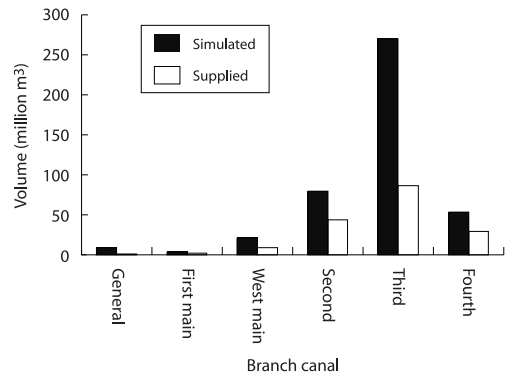

Figure 8. Comparison of water actually supplied and IMSOP-simulated irrigation demand in different branch canals of the Zhanghe Irrigation System, central China in 1999

Table 2. Supply:demand (IMSOP) ratio in different branch canals of the Zhanghe Irrigation System, central China

Canal branch	1999	2000	2001	2002
General	0.11	0.23	0.37	0.10
West main	0.55	0.22	0.59	0.07
First	0.40	0.42	0.48	0.17
Second	0.54	0.84	0.43	0.12
Third	0.32	0.49	0.45	0.20
Fourth	0.53	0.85	0.68	–

The amount of water allocated for irrigation from the Zhanghe reservoir has fallen from 171 million m^3 in 1999 to 38.3 million m^3 in 2003. The ZIAB has allocated to hydro-power generation the water now not used for irrigation.

Order delivery

Historical water order data were analysed to determine how well the managing agency functions in

delivering water orders to farmers. The management stations were able to deliver more than 70% of the orders on the same day. Only about 10% of the orders were delivered 3–5 days after being placed (Figure 9). The delay was mainly due to the fourth main canal office being unable to supply water if the aggregate volume order by the stations was less than a minimum threshold amount. The critical discharge or water volume is set in relation to that of the initial water loss and filling of the canal in each delivery. If the cumulative water ordered by the farmers is less than this threshold value, the management office will wait for more orders to accumulate to reduce the initial losses and dead canal storage.
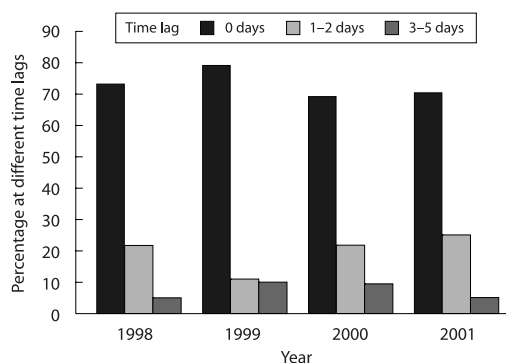

Figure 9. Percentage of water orders delivered in the Zhanghe Irrigation System, central China at various time lags

Comparison of historical supply and order volume

Historical water order data were collected from Wenjiaxiang and Anzhankou stations and aggregated. A comparison of the volume of water ordered and the volume of water abstracted in this section of the fourth main canal as calculated from the canal water balance reveals a large oversupply varying between 29% and 66%. This includes canal filling and other losses, which may account for a large proportion of this amount but were not disaggregated in this study (Figure 10). In a single irrigation event during 2004, 300,000 m^3 (20%) of a total supply of 1,700,000 m^3 was estimated to consist of canal filling and other losses. This large volume can be traced to with the configuration of the hydraulic infrastructure. The canal is very long (25 km) and the flow is controlled by only one cross-regulator located towards

the tail end of the canal section. Moreover, cross-regulators in this system are not used to regulate water levels but rather to switch flow on and off to the lower part of the system. A further reason is the poor condition of the canal. A survey of the longitudinal and cross sections of the east branch canal shows that the canal cross section varies widely every 10–20 metres.
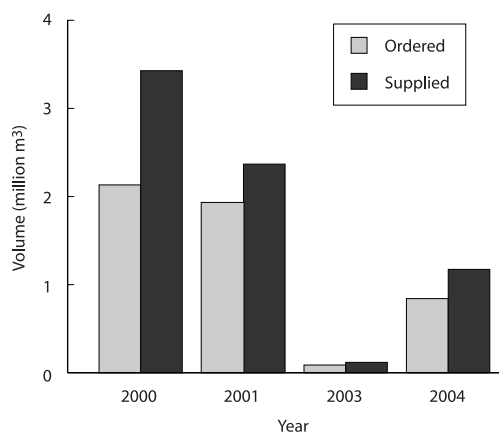

Figure 10. Comparison of aggregate volume of water ordered and supplied in Wenjiaziang and Anzhankou service areas in the east branch canal of the Zhanghe Irrigation System, central China

Canals in this system are relatively long and, in some cases such as the east branch canal, water must be supplied to small reservoirs or ponds demanding a large amount to fill dead canal storage. Lengshui and Heji townships are the main irrigation areas on the east branch canal located in the end of the canal where there are many local sources of water. While these areas may delay water ordering, areas in the upstream reaches of the east branch canal such as Wenjiaxiang and Anzhankou must incur periods of droughts because downstream orders do not meet the critical flow.

Infrastructure management

A further objective of the project was to develop an infrastructure management strategy to determine the cost of service provision that will ensure sustainability of the infrastructure. An adaptive asset management framework developed in ACIAR project 9834 in Vietnam (Malano et al. 2004) was implemented on a pilot basis in the east branch canal.

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Asset survey

Irrigation and drainage infrastructure often consists of a large number of individual assets dispersed over large areas. The ZIAB does not have any database of the assets it owns. A major component of asset management planning is the assessment of the extent, function, condition, value and performance of the individual assets (Burton et al. 2003). The task is usually cumbersome and accounts for a large proportion of the cost of implementing an asset-management program. The project employed a rapid data collection technique using GPS technology (Malano et al. 2005). This approach involves a seamless integration between the collection of field data and asset condition information with geographic information system (GIS) and asset management software. The irrigation and drainage infrastructure surveyed in the east branch canal consisted of 69 offtakes, 4 regulators, 27 pedestrian bridges, 20 vehicle bridges, 11 pumps and 22 km of canal.

Asset-management software

An effective asset-management information system must be capable of integrating data collection, storage, retrieval and processing. Asset data are stored in an asset register which enables asset operators to maintain up-to-date records of the existing asset base. An asset-management software program called Asset Manager[©] was developed to facilitate the rapid recording, update, retrieval and manipulation of the existing asset base. The software was applied on a pilot basis to the east branch canal (the fourth main canal bifurcates into an east branch canal and north main canal). The Asset Manager software was adapted for use by ZIS staff.

The Asset Manager software has three important components: a graphical user interface, a model base and a GIS-based database management system (Malano et al. 2005). A spatial database related to canal network and locations of structures was created by digitising the original system's maps using ArcView™ GIS software. The data collated by GPS-based asset survey can be directly geo-referenced to the asset GIS. Asset condition attributes and asset cost data, together with design conditions, can be uploaded using the GUI. The GUI was built using Map Objects[3] and Visual Basic[4] and is mouse-driven

with pop-up windows and pull-down menus. The map objects enable the user to display the GIS files so that the database can be retrieved and updated easily using the graphical interface. The results can be graphically displayed or exported into a spreadsheet for further analysis.

The software has special functionality to search and update asset information. Based on the asset database, asset strategy modelling can be carried out by calculating and tallying asset categories and conditions, future asset investment and asset financial annuities. The software is designed to help irrigation companies monitor the condition of their assets and carry out financial analysis calculations to develop service costing and pricing policies.

The software was applied on a pilot basis on the east branch canal system to provide a representative model for the whole Zhanghe system. The asset survey was confined to the canal sections under the control of the Anzhankou and Wenjiaziang management stations, but the processes for describing structures and asset conditions are similar in all the other branch canals in Zhanghe. The software is designed so that it can be extended to other parts of the system without changes.

Renewal strategy and annuity cost

Sustaining the infrastructure in perpetuity requires adequate provisions to carry out appropriate interventions such as replacement and modernisation when required (Malano et al. 1999). Asset Manager was used to analyse the long-term investment provisions necessary to achieve sustainability. Figure 11 shows the tally of asset condition for east branch canal. Offtakes, regulators, culverts and bridges are in fair condition, with some assets in poor condition and requiring renewal in the short term. In the east branch canal, 89 assets are in condition 1 (good), 33 in condition 2 (fair), 13 in condition 3 (poor), and 4 in condition 4 (very poor). The assets include offtakes, regulators, bridges, pumps and canals.

The investment profile shows that a large investment is required in the next 15 years, as certain group of assets will reach the end of their lives within that period. The irrigation management company will need to invest 0.40 million Yuan[5] in the next 15-year period to replace assets in poor condition. This will translate into high cost recovery annuities during this period.

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[3] Map Objects is a trade mark of ESRI
[4] Visual Basic is a trademark of Microsoft Co.

[5] 1 US$ = 8 Yuan

The Asset Manager software calculates asset annuities based on the asset condition. The linear depreciation, full and partial annuity for the east branch canal system are estimated on average as 110, 235 and 140 Yuan per ha (US$13.7, 29 and 17.5/ha), respectively, over the next 15 years. An interest rate of 5% and inflation rate of 3% were used in these calculations. Canal excavation costs occur only once in the life of the asset and are therefore not included in the renewals calculation, although the initial cost must be taken into account. On the other hand, the cost of lining is included in the annuity calculation as it requires future replacement and regular maintenance.

Financial viability and service costing

Data were obtained from the company's financial balance sheets from 1999 to 2003. The company's financial analysis showed that revenues for the fourth main canal office had declined from 5.1 million Yuan in 1999 to 4.6 million Yuan in 2003 (11%). This can be ascribed mainly to a reduction in revenues from irrigation from 0.66 million Yuan in 1999 to 0.02 million in 2003 (Figure 12). As indicated earlier, the revenue from irrigation water fees was nil during 2002 as no irrigation water was demanded. In typical years, however, irrigation water use accounts for as
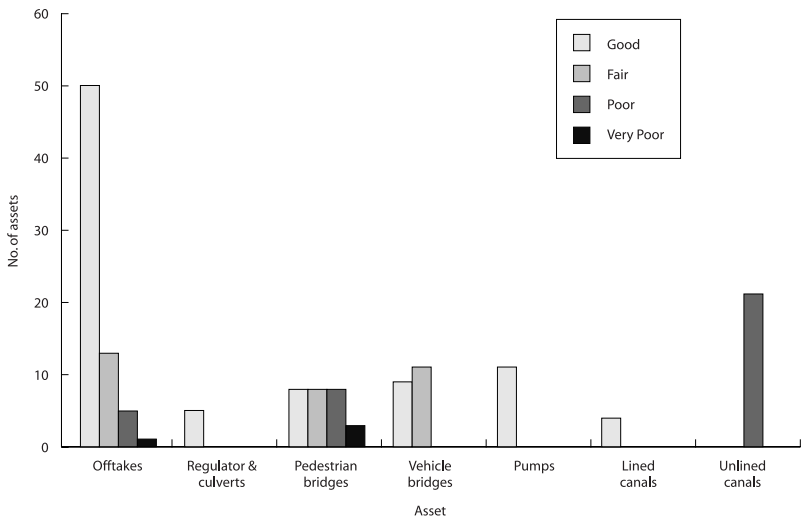

Figure 11. Tally of asset condition in the Zhanghe Irrigation System, central China
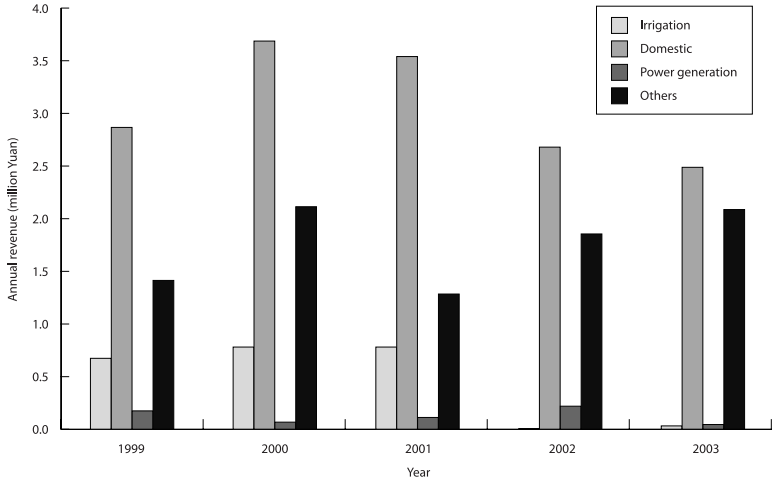

Figure 12. Annual revenue from different users of Zhanghe Irrigation System water

much as 70% of the total water allocated to the fourth main canal. Income from household and industrial supply remained nearly constant over the same period. Although agriculture is the largest water user, the revenues from irrigation water supply account for only 10% of the total income (in 1999). During 2003, irrigation receipts contributed only 0.5% of the total revenue.

Total expenditure rose between 1999 and 2003, from 2.04 million to 3.9 million Yuan. Two expenditure items account for most of the costs: wages and salaries and miscellaneous expenses. Repair and maintenance expenditure declined over the same period. The current maintenance expenditure represents only 1.4% of the total expenditure.

The sustainability of the company and system operations, however, depends on the ability to support its recurrent cost and sustain its asset base in perpetuity (Davidson et al. 2005). From a company perspective, this implies the ability to renew its asset base when the current assets reach the end of their economic life. If the capital fully depreciates and eventually breaks down, it will need to be scrapped or rebuilt.

The financial costs associated with a sustainable operation of the irrigation company can be grouped into eight categories:

• asset costs
• personnel costs, including staff salaries
• repairs and maintenance
• administration
• insurance
• payment of loans
• taxes
• miscellaneous.

The comparison of the total service costs, including the asset replacement annuity for the period 1999–2003, are presented in Figure 13. The capital costs associated with the renewal of the asset base were estimated to average 235 Yuan/ha. It is important to note that only irrigation assets are represented in the asset annuity. Headworks and other company assets used to supply urban and industrial water are not included.

The full cost of providing water delivery service by the fourth main canal office is estimated to have been 5.06 million Yuan during 2003 (Figure 13). The ratio of irrigation revenues to irrigation service costs is very low. In 2003, when only one irrigation event was supplied by the office, irrigation revenues accounted for only 0.6% of the total cost.

The nominal irrigation water fee set by the Zhanghe Irrigation Administration Bureau is 0.04235 Yuan/m^3. However, the actual revenues from water fees, calculated on the basis of the water diverted for irrigation in the fourth main canal, is 0.01 Yuan/m^3, or about 25% of the nominal water fee. This may be due to the large losses in the canal, lack of proper devices to measure the amount supplied and low revenue collection level associated with the post-delivery payments.
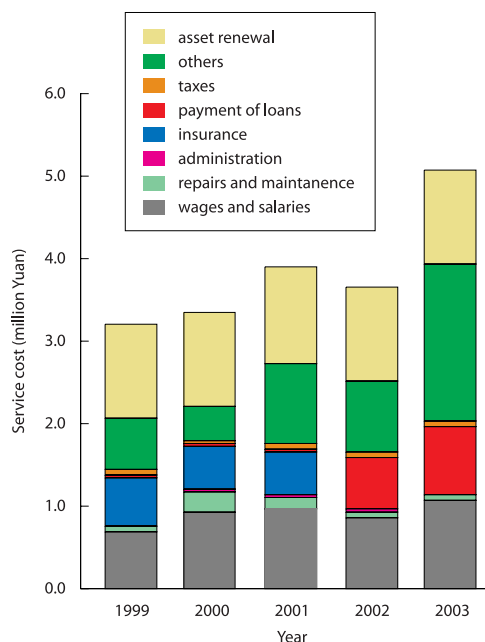
Figure 13. Renewal-based service cost for the fourth main canal of the Zhanghe Irrigation System, central China

Adoption of results

An important aim of the project was to promote the adoption of system management innovations in other irrigation schemes in China. Melbourne University staff conducted training for Wuhan University staff and Zhanghe staff on the use of GPS for rapid asset data collection, on operation modelling with IMSOP and in the use of Order Manager. Adoption was also facilitated by translating all software interfaces and user manuals into Chinese.

As a result of the project training activities, ZIAB staff have initiated the extension of the integrated

operational framework to the whole of ZIS. The project staff laid-out a GIS for the entire main system to provide a platform for extending the results to the whole of ZIS. ZIAB staff have completed the asset survey of the whole of ZIS, and Wuhan University staff are helping them to modify the Asset Manager software to extend the model to the whole system. The future application of the improvement framework to systems in the rest of China can be supported through Wuhan University and ZIAB staff who were involved in the project.

Improved scheduling of supply requires improved quantification of irrigation demand which can be achieved through better modelling. The long-term sustainability of the company depends on the ability to support its recurrent costs and sustain its asset base in perpetuity. In practice, the skill level required to carry out these tasks may currently be beyond that of the staff of many irrigation management companies. Company management and operational staff would need to develop a clear understanding of the operational objectives, infrastructure sustainability and mechanisms to improve them. It would need a rigorous training program to achieve the management capability. A provincial or country level policy to implement these technical and management improvements would ensure success.

Conclusions

This research has provided a useful and practical methodology to diagnose deficiencies in the irrigation system infrastructure and its operation, and to establish the basis of a management system to provide defined levels of service to users. The methodology is aimed at ensuring the sustainability of existing and rehabilitated systems in China. The results of the project are both useful and applicable to millions of hectares of irrigated areas in China. The IMSOP and Asset Manager models provide a flexible approach to the operation of irrigation systems and management of infrastructure. They enable company managers to diagnose and improve the operation of their systems.

The following are the major impacts resulting from the operational and management improvement process:

• The implementation of the modelling framework to a pilot area in ZIS enabled the identification of shortcomings in the operation of the irrigation

system. The application of the IMSOP and Order Manager models demonstrated an improvement in the level of operational management and identified specific shortcomings in the hydraulic control infrastructure of the pilot area.

• The amount of water used for irrigation is steadily declining. Farmer demand for irrigation water has fallen considerably in recent years as farmers have become more reliant on rainfall and local water sources for irrigation in response to recent change in government policies. This could imply, among other things, a marginal utility of irrigation in this region.

• Comparison of historical water order data revealed that the Wenjiaxiang and Anzhankou areas incur periods of water deficit because of inadequate routing of water orders from these two sections. The main reasons are the Lengshui and Heji sections delaying orders on the expectation of forthcoming rainfall precluding the volume of orders reaching the delivery threshold.

• The pilot asset-management program developed as part of this project enabled the managing authority to plan a long-term strategy for the maintenance and replacement of infrastructure assets in the system. The asset-management program enables management to estimate the actual cost of providing irrigation and drainage services and raises awareness of the financial viability of the authority in the long term. The program enables the identification of full service cost and the shortfall in the current revenue structure.

• The analysis of the financial performance of the ZIS showed that the income from supplying irrigation water has been steadily declining over the last 5 years by 65% to only 1.1% of the total income. This is a threat for the sustainability of irrigation in future.

All these project findings can readily be incorporated into the formulation of future policy for the irrigation sector in China. The project trained local researchers and managers to the point where they can, without outside assistance, extend the modelling to the whole of ZIS system or any other systems in China. The ZIAB has initiated the application of the improvement and modelling framework to the rest of the Zhanghe system and an asset survey of the whole of the system is in progress.

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Economic and institutional considerations for irrigation water savings

Shahbaz Khan[1]

Abstract

Some measures that may improve irrigation water productivity in agriculture are canal lining, irrigation scheduling, advanced irrigation technologies, improved cropping patterns and conversion to crops with higher economic returns. Each of these options has its own economic merits and institutional issues. This paper summarises an economic evaluation of water-saving interventions at the field, irrigation area and catchments levels. Supply and demand theory is used to explore how to internalise the social costs created by irrigation activity and saving of associated losses that burden the local and regional environment.

A market-based approach which utilises a 'water leasing' and 'preferential right to access saved water' is argued to take advantage of the market mechanisms for the preservation of the environment. Private–public investment for 'efficient' water supplies which can account for third-party impacts needs to be established to promote investment in water-saving technologies. This will help provide secure 'saved water supplies' for 'water efficient irrigation and environment', especially during drought because of real water savings from 'fixed system losses'.

灌溉的经济和体制问题

摘要：改善农业灌溉用水生产率的措施有渠道衬砌、灌溉计划、高技术灌溉方法、改善作物结构和种植高价值作物。这些选择都有其各自的优点和体制问题。这篇文章总结了田间、灌区和流域节水措施的经济评价。应用供需理论探讨如何消化灌溉活动和减少相关损失给当地和区域带来的社会成本。探讨应用"出租水权"和"获得节约下来水的优先权"等基于市场的方法，以便利用市场机制保护环境。为了促进对节水灌溉技术的投入，需要建立能体现对第三方影响的私人—公共高效供水投资。由于是从"固定的系统损失"当中真正节约了水，这将有助于保障为"高效灌溉和环境"提供"节约下来的供水"，特别是在干旱季节。

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Introduction

As elsewhere in the world, Australia's irrigation systems suffer from problems associated with losses in storage and conveyance, on-farm losses and variable water-use efficiency. In the Murray–Darling Basin (MDB), it is widely accepted that 25% of diversions for irrigation are lost during conveyance in rivers, 15% are lost from canals and 24% are lost on-farm, meaning that only 36% of irrigation water is actually delivered to plants. Such losses are typical across the world (Table 1). The data in Table 1 for the Murrumbidgee Irrigation Area (MIA) do not include river conveyance losses and indicate on-farm losses better than the overall MDB average (Khan et al. 2004). However, given that the world will need to feed 1.5–2 billion extra people by 2025, there has to be scope to reduce water conveyance losses and irrigation efficiency worldwide.

In recent years, there has been a growing concern in Australia about the effect that major diversions of water for irrigation are having on the environment. This is creating further 'economic' competition for water, along with demands from urban and industrial users. Given that rural water use (predominantly irrigation) accounts for over 70% of Australia's total water use, a figure similar to that in most Southeast Asian countries, and given the increasing scarcity of the resource due to climate change and other environmental factors, it is not surprising that pressure is increasing on irrigators to increase water-use efficiency and to achieve true water savings by conserving water otherwise lost through non-beneficial evaporation or seepage to saline aquifers.

The key to achieving real and substantial water savings lies in the technical, economic and institutional assessment of water-saving options in a whole-of-the-system context. In the Murrumbidgee Catchment, adoption of a systems approach showed that accounted losses greater than 300 GL can be saved (Khan et al. 2005 a,b).

Economic issues

To target on-farm and regional water savings, it is hypothesised that the marginal costs for saving irrigation water will increase with the volume of water saved and that it is possible to formulate irrigation-water-saving cost curves for traditional or alternative irrigation technologies to help shift these cost curves to lower costs, as illustrated in Figure 1. Figure 1 shows a simplified schematic of the marginal costs and benefits for the current cropping systems. 'X' represents the current viable levels of water savings which can be shifted to the right through the low-cost alternative technology.
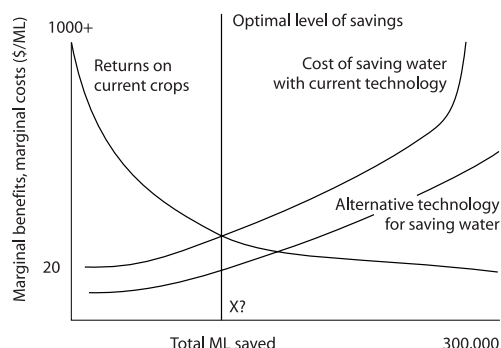

Figure 1. Benefit–cost curves for water saving technologies

The economic analysis of on-farm conversions to save each extra megalitre of water show that the cost increases with the total savings, as shown in Figure-2. Typical capital costs to save a megalitre of water vary from less than $2000 to over $7000 depending upon soil type, crop and irrigation technologies used.

Break-even analysis (not presented here) shows that the break-even interval for conversion from flood to pressurised irrigation systems is too long

Table 1. Surface water irrigation efficiency in three irrigation systems

Key indicators	Liuyuankou, China	Rechna Doab, Pakistan	Murrumbidgee Irrigation Area, Australia
Area (ha)	40,724	2,970,000	156,605
Losses from supply system (%)	35	41	12
Field losses (%)	18	15	11
Net surface water available to crop (%)	46	32	77

(greater than 15 years). There is a need to reduce the break-even period by considering leasing of water for the environment from farmers at around $300/ML for a fixed period of 5–10 years after which the water can be returned to the farmer, and the government can then lease the next lot of water from another group of farmers. This will help remove barriers to the adoption of irrigation technologies, reducing local and regional environmental impacts and securing water for better ecological futures.
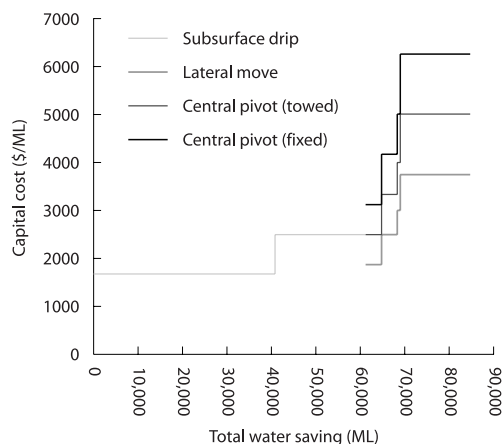
Figure 2. Capital investment and total water savings by for advanced irrigation technologies in the Murrumbidgee Irrigation Area, Australia

The economic analysis of alternative water-saving technologies for channels shows that the cost of saving a megalitre of water increases with the total savings, as shown in Figure 3. Typical capital costs to save one megalitre of water vary from less than $500 to over $4000 depending upon losses per unit length and the seepage-reduction method used.

A similar economic analysis in the Liuyuankou Irrigation System in China indicates that, to save about 20 million m^3 of water over a 60 km length of channel, capital investment of 3.8 Yuan/m^3 would be required. The current water productivity is 1.35 Yuan/m^3. The capital cost of water saving when compared to Australian costs is $A619/ML. With the current water productivity it is not feasible for farmers or irrigation agencies or companies alone to achieve water savings in China. There is a need for private–public investment and realisation of third-party beneficiaries such as the environment and downstream water users to share the water saving costs.
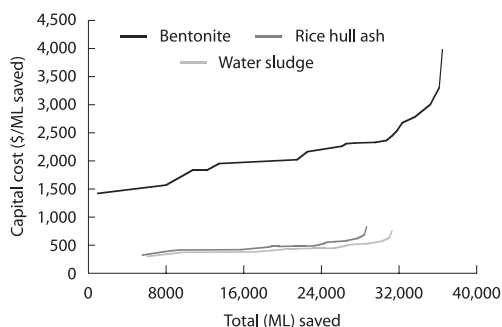
Figure 3. Capital investment curves for saving seepage losses

In Australia there is general feeling that water savings that cost more than $1000/ML are not viable. The break-even analysis of different channel-lining materials by Khan et al. (2004) shows that the price of saved water on an annual basis needs to be from $30/ML to over $200/ML to break even within the design life of the project. This investment can be achieved in either of two ways: by using the saved water on higher-value crops, or by including the costs of saving water in the overall water supply charges, with a proportionate cost-sharing arrangement. Water delivery charges, for example, will increase by $5–15/ML/season to provide water more efficiently (the current water delivery charges is less than $20/ML/season). This will also reduce waterlogging and salinity-abatement costs (current estimates of costs for waterlogging and salinity abatement are $10–200/ML or recharge/year). The proportional cost to be paid by the farmer may be less than discussed here if it can be shared with the wider environmental beneficiaries. There is a need to promote a water efficiency culture through *preferential rights of access*, by providing a greater security to farmers and irrigation companies investing in water-saving technologies.

Institutional issues

Who saves and who owns the water losses?

One of the key impediments to achieving real water savings is the issue of ownership of losses and how to reallocate on-farm and off-farm water savings. In New South Wales, Australia conveyance system, losses are collectively 'owned' by the farmers through the privatised irrigation companies, in terms of a conveyance allowance. There is a provision in the Mur-

rumbidgee Water Sharing Plan (DLWC 2003), for example, for a conveyance access component for the Murrumbidgee Irrigation company up to 243,000 ML to make up for the transmission loss in water accounting. Similarly, farmers are given water entitlements irrespective of the actual crop water use. This water entitlement is used to irrigate crops and results in evaporation and deep percolation losses. If farmers invest in new technologies to save water losses, they may wish to increase their area of production or sell the saved water in the open market.

Institutional complications are caused by the common-pool nature of the irrigation supply infrastructure and deep drainage below the root zone. This may lead to lack of collective action. Managing irrigation systems requires coordinating the actions of many users sharing the same resources of water and irrigation infrastructure. Users receiving the direct benefit are likely to ignore the effect of their actions on the common pool when pursing their self-interest. Environmental sustainability of surface- and groundwater and maintenance of irrigation infrastructure resources are therefore at risk of becoming a 'tragedy of the commons'.

To explore reasons for the lack of action by farmers and irrigation companies reference is made to the long break-even interval (greater than 15 years) to achieve net profit from investment for conversion from flood to pressurised irrigation systems in case of the Murrumbidgee catchment. Farmers also have little interest in permanently surrendering their water entitlements in exchange for capital incentives for new technology due to uncertainty arising from current and proposed water reforms.

A business case for achieving water savings at the farm, regional and basin level has already been established by the Pratt Water Feasibility Study in the Murrumbidgee Catchment. This seeks a uniform national water efficiency and environmental regulatory framework using a Council of Australian Governments framework (Pratt Water Group 2005).

The Australian Government recently initiated a National Water Commission (NWC) to accelerate reforms. At the water distribution and on-farm level, the focus of reform and research is on the identification and reduction of leakage and water losses, the determination of water benefits and improved water accounts, improved efficiency of water delivery systems including the change-over from gravity-fed to pressurised delivery systems and better design of irrigation requirement and delivery to the root zone,

as well as on the development of market-based instruments to facilitate improved natural resource management. However, there are still major differences in productivity across farms, so considerably more effort is also required at identifying the biophysical, management practices and social reasons behind this variability in order to get all enterprises working more productively.

Conclusions and way forward

In order to achieve true water savings, a systems approach is necessary to target real water savings and to remove technical, economic and institutional barriers.

The on-farm and off-farm water saving costs vary from less than $50/ML to well over $5000/ML. Such investments can be possible either by using the saved water on higher-values crops or by including saving costs as part of the overall water supply charges with a proportionate cost-sharing arrangement. There is a need to reduce the break-even period by considering 'leasing of water' for the environment from farmers at around $300/ML for a fixed period of 5–10 years after which the water can be returned to the 'owner' and government can then lease the next lot of water from another group of farmers.

If the water-saving technologies are considered on their own, the costs involved will be too high to attract any substantial investments by the individual farmers and irrigation companies. This is mainly because the irrigation supply systems represent a shared and jointly owned common pool resource. There is possibility of inaction among local, regional and national actors, leading to market failure and a classic tragedy of the commons. Institutional reforms aimed at minimising risk of market failure driven by the tragedy of commons are required to secure a win–win situation for all stakeholders.

Due to low commodity prices, farmers and irrigation companies on their own will be unable to achieve water savings. Unless water saving costs and benefits are shared by all players in a catchment, real water savings are not possible. Private–public investment models aimed at providing preferential access rights to those who save water by investing in water-saving technologies may be one of the ways forward. There is a need for realising benefits to the environment and downstream water users to share the water saving costs.

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Water reallocation in northern China: towards more-formal markets for water

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Abstract

Rapid economic and population growth has driven increasing demand for water from industrial and urban sectors, and placed pressure on resources available for agricultural production. While there has been widespread economic liberalisation of commodity markets, access to natural resources such as land and water remains constrained. The capacity to reallocate water resources to best meet these competing demands is an important aspect of both water and agricultural policy reform in northern China.

This paper explores the institutional framework for water management in northern China. Data from farm household and water manager surveys are used to make preliminary estimates of the benefits of water reallocation in the Yellow River Basin. Using information from this case study, future directions for water property rights and policy are discussed in light of China's commitment to a more efficient allocation of water resources both within and between irrigation districts, and between competing uses.

华北地区的水资源重新配置：走向更为正式的水市场

摘要：经济和人口的快速发展推动了工业和城市需水的增长，给农业生产所需资源增加了压力。在商品市场的经济自由化已经得到扩展的情况下，获得土地和水等自然资源仍然在收到限制。为了在最大程度上满足这些竞争需求，在华北地区重新配置水资源的能力是水和农业政策改革一个重要的方面。

这篇论文探讨了华北地区水管理的体制框架。用从农户和水管单位调查来的数据分析评价黄河流域水资源重新配置的效益。应用这项研究的资料，按照中国将在灌区内、灌区之间以及不同竞争用途之间更为有效地配置水资源的承诺，本文讨论了未来水权和政策的发展方向。

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Introduction

Since the mid 1970s, China, particularly the regions of the Huai, Hai and Yellow River basins, has faced water shortages of growing magnitude. Rapid economic and population growth has driven increasing demand for water from industrial and urban sectors and placed pressure on resources available for agricultural production. Historically, the transfer of water from agriculture to urban and industrial use has caused social unrest, with disputes and clashes erupting as farmers struggle to retain access to water resources. Further, the potential to improve farm incomes by moving from staple agricultural commodities, such as wheat and maize, into higher-value crops such as horticulture has also placed pressure on developing mechanisms to reallocate water used for irrigation within the agricultural sector, including between regions.

In response to concerns of water scarcity and allocation, water policy over recent decades has shifted from investing in large storage and delivery infrastructure and water conservancy projects to policies and institutions designed to ration and allocate existing resources more efficiently. The policy shift from infrastructure projects that increase water supply to improving water allocation represents a major ideological shift in water management in China. Consequently, the definition and establishment of water property rights that underpin these reallocation mechanisms are important components of both water and agricultural policy reform.

This paper explores the institutional framework for water management in northern China. This region was selected because it contains around two-thirds of China's cultivated land but less than a quarter of the nation's water resources. Almost 50% of the nation's gross domestic product is generated in northern China and the region is a significant producer of wheat and maize (Ministry of Water Resources 2000). Data from farm household and water manager surveys are used to make preliminary estimates of the benefits of water reallocation in the Yellow River Basin. Using information from this case study, future directions for water property rights and policy are discussed in light of China's commitment to a more efficient allocation of water resources both within and between irrigation districts, and between competing uses.

The Yellow River Basin

The Yellow River is the second longest in China, with a total length of almost 5500 km (Figure 1). The Yellow River Basin covers an area of 795,000 km^2 and is characterised by varying climate and relief. The basin can be divided into three distinct reaches — the upper, middle and lower — according to those characteristics. The upper reaches where the river is sourced are mountainous with deep valleys until the river flows across the alluvial plains of Ningxia and Inner Mongolia. The reach from Lanzhou to the Mongolian steplands receives minimal rainfall but faces large irrigation demands. The middle reaches, between Hekouzhen and Huayuankou, encompass the major irrigation areas of Shanxi and Shaanxi that are fed by the Yellow River's two major tributaries, the Fen River and the Wei River. Massive amounts of loess soil enter the main stem and tributaries, which results in sediment loads unprecedented in the world's major waterways. The lower reaches stretch from the Taihang Mountains to the Bohai Sea. Much of the alluvial plain area of the lower Yellow River area is below river bed level and the river is 'suspended' (IWMI and YRCC 2002; YRCC 2005).

Annual precipitation distribution falls from 600 mm to 200 mm more or less progressively from southeast to northwest. Annual average run-off is around 58 billion m^3. Several large storages provide flood control, ice-run control, sediment mitigation, hydropower and water-supply services. Water consumption is estimated to be around 31 billion m^3, with agricultural uses accounting for around 80% of total water consumption in 2000. The average per capita share of water resources in the Yellow River Basin is less than 20% of China's average, and considerably less than that in the rest of the world (IWMI and YRCC 2002; YRCC 2005).

The Yellow River Basin is regarded as the cradle of Chinese civilisation and irrigated agriculture has been practised there for thousands of years. Massive government investment in irrigation infrastructure increased rural livelihoods and agricultural output in the 1960s and 1970s. Irrigated agriculture has expanded significantly over the past four decades and new irrigation and agronomic technologies have increased yields considerably in some areas. Key agricultural data for nine provinces in the Yellow River Basin in 2002 are given in Table 1. Irrigation requirements vary considerably because of the large variations in soil and climatic conditions across the basin. This is, in part, reflected in the

variation in crop water use between provinces. Based on provincial level data, per hectare crop water use in upstream provinces (such as Qinghai, Ningxia and Inner Mongolia) is higher than in other provinces. This may also be due to these upstream regions having greater access to water resources. Climatic conditions in the lower reaches, such as in Henan and Shandong, mean that crop water requirements are lower than in other parts of the basin. Due to variation in irrigation conditions and other factors, land use intensity and cropping structures in these regions also vary. More favourable agronomic and climatic conditions mean that farmer incomes are higher in the downstream provinces (IWMI and YRCC 2002; Huang et al. 2006).

While there are still opportunities for water savings, utilisable water resources are currently fully exploited in the Yellow River Basin, so meeting new demands will almost certainly be achieved by reducing supplies from other sectors. As agriculture is a large water user, further reductions in supply seem inevitable, although this will have implications for rural livelihoods and the long-standing policy of food self-sufficiency. One of the key policy challenges is how to reallocate water supplies while maintaining rural incomes and agricultural output.

The focus of the remainder of this paper is to assess the role that water property rights could play in facilitating water reallocation, and to estimate the impacts on farm household income of reallocating water in the Yellow River Basin.

Water management in China

Despite the liberalisation of the broader Chinese economy, China does not currently have formal water markets that are supported by clearly and universally assigned water property rights. There are, however, non-market mechanisms for assigning water use rights and allocating water. Usufructuary rights to water use have evolved either explicitly through laws and regulations or implicitly through conventions. These rights are generally assigned based on one of three systems: first come-first served allocation ('prior appropriation' rights); allocation based on proximity to flows ('riparian' rights); and public allocation. The focus of this paper is water that is publicly allocated and distributed: public authorities allocate water using guidelines or laws establishing priorities (Holden and Thabani 1996; Haddad 2000).
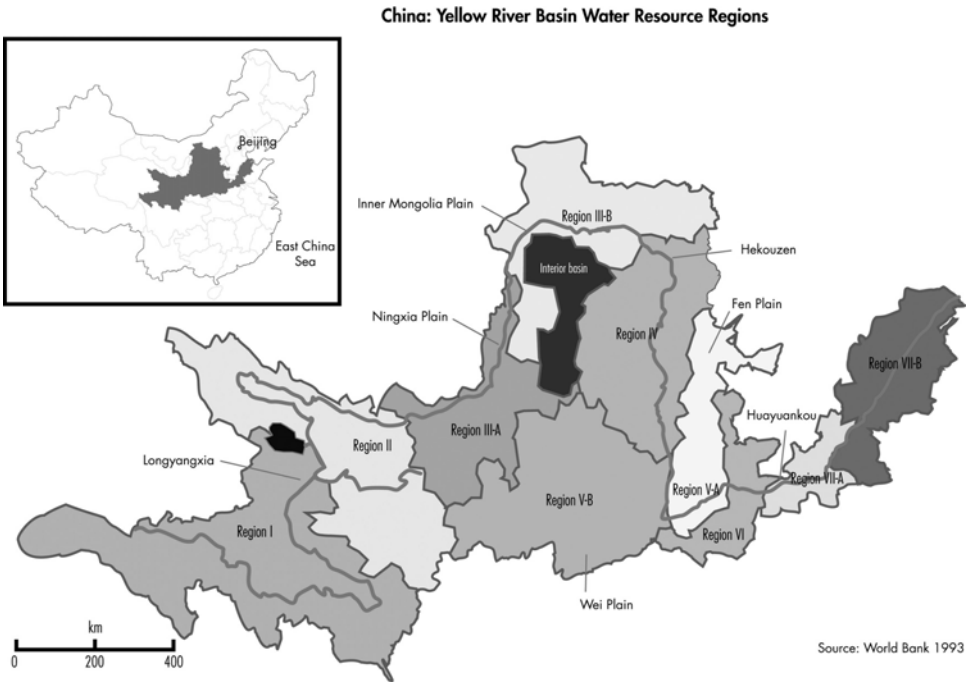

Figure 1. The resource regions of the Yellow River Basin, China

Table 1. Agricultural water use and farmer income, 2002

Province	Agricultural water use (10^9 m^3)	Irrigated area ('000 ha)	Crop water use (m^3/ha)	Farmer income (Yuan/year)
Sichuan	122.25	2500.6	48,888	2108
Gansu	97.25	988.3	98,401	1590
Qinghai	20.36	193.5	105,220	1669
Ningxia	76.03	410.0	185,439	1917
Inner Mongolia	448.85	2537.6	176,880	2086
Shanxi	35.50	1103.7	32,165	2150
Shaanxi	54.62	1314.7	41,546	1596
Henan	145.74	4802.4	30,347	2216
Shandong	188.27	4797.4	39,244	2948

Data source: China Statistic Yearbook, 2003

The Water Act, decreed in 1998 and amended in 2002, states that the state owns water and that water rights are not associated with land rights. Land is owned either by the state or by the collective. The state department exerts ownership over water resources on behalf of the nation. There is a vast and complex bureaucracy to manage water resources. It is designed to manage often conflicting policy goals of allocation, management and pricing of agricultural, urban and industrial water, water conservation, flood and sediment control, and power generation. Surface- and groundwater, for example, are managed by different institutions, despite the interrelatedness of the use and management of these two resources. As China's state and administrative system is continuing to evolve to a more decentralised structure, there is considerable regional diversity in the details of governance structures, particularly as the definition of roles and scope of the various institutions develops (Mollinga et al. 2003).

The Ministry of Water Resources formulates surface-water-related policies and medium- and long-term development plans designed to balance water conservation and demand management goals. Other agencies, including the Ministry of Land Resources, have jurisdiction over access to groundwater. The Ministry of Water Resources administers withdrawal permits under which irrigation districts are granted a right to withdraw a fixed amount of surface water from the river or storage. Irrigation districts draw water from the river and distribute it along a main canal to villages via a metered gate. The village maintains the canal network, and all of the water that flows into the village is for the exclusive use of the village's own residents. This water does not have to be shared with villages either upstream or downstream. Typically, in most villages, the village leader or water officer in the village committee takes charges of the village's water management system and assesses water fees (Wang et al. 2005).

The current charging policy for water varies across the basin although prices are usually uniform for a specific end use, such as agriculture, in a specific province. The central government has encouraged the adoption of volumetric surface water charging, but as plots are so small, it is not feasible to charge individual farmers according to how much water they use. Current charges take into account both water scarcity and the ability of farmers to pay. They remain low, however, particularly in comparison to domestic and industrial water charges. Consequently, there is little incentive for farmers to conserve water (Lohmar et al. 2003; Wang et al. 2005).

Outside of the central government, there are many water management institutions at the provincial, prefectural and county level that also influence water policy and management. The Yellow River Conservancy Commission is the overall planner and regulator of water in the basin. The duties of the provincial water bureaus include planning, survey, design, construction, operation and management of irrigation, drainage, flood control works and rural hydropower. The water resources bureaus at the prefecture and county levels are directly responsible for constructing and maintaining irrigation infrastructure, associated flood-control facilities and medium-size reservoirs. Most county offices have water resource stations in each township that construct and maintain branch canals and small reservoirs. These offices interact with local villages (Bin 2003; Lohmar et al. 2003; Wang et al. 2005).

A formal legal structure has not been an important component of water property rights and local party leaders often handle disputes and conflicts on a non-legal basis. As the complexities of these disputes increase, transactions costs escalate and non-formal means for resolution have become less appropriate.

China is slowly reforming its water laws, institutions and policies to better manage water and other natural resources. Water management policy in the Yellow River Basin is now predominately focused on reallocating water resources under conditions of scarcity rather than developing new sources of supply through large infrastructure projects. There is a focus on integrated water management and allocation, the enhancement of water-use efficiency, strengthening governance in water resources planning and coordination, and poverty alleviation. A national water resources plan, which was due to be completed by the end of 2005, is being promoted as a tool with components of water resource assessment, utilisation and development to progress toward integrated water management. A preliminary legal and policy framework under the Water Act, and others, has been established to implement more-formal water rights regimes and water reallocation mechanisms (Zhang 2005).

Water rights are not transferable under the Water Act. There have, however, been many attempts to reallocate water in China, few of which have been successful due to lack of enforcement and poor incentive structures and, in some instances, the lack of an institutional framework to do so. In 1999, for example, a program was initiated to alleviate water shortages in the downstream reaches of the Yellow River. It was proposed that reductions in water allocated to each province in the upstream reaches be introduced gradually. The volume of the reductions was based on an evaluation of demands claimed by provincial officials in the lower reaches and the feasibility of being able to save water in each of the upstream provinces. Water prices were also increased in the upper reaches to provide a further incentive to save water (Wang et al. 2005).

A further example of an attempt to reallocate water was a proposal to transfer water between bordering cities, Dongyang and Yiwu, in the upper reaches of the Jinhua River in Zhejiang Province. The proposal included an investment by the municipal government of Yiwu in a reservoir owned by Dongyang City in exchange for the right to water supply of 50 million m^3 each year. While this transfer appeared to have the potential to improve the social and economic effi-

ciency of resource utilisation, the transfer did not go ahead because neither the buyer nor the seller of the water had the legal right to surplus water usage. Consequently, there was no legal support for the 'permanent' transfer of water, which could undermine the transaction in the future. As such, the transfer could be considered to be only a 'debt use right contract to water' since the permit to use water could not be transferred (Bin 2003). Although this example is drawn from outside of the Yellow River Basin, it shows how inadequate legal and institutional frameworks can preclude water transfers, even though they made lead to a more efficient outcome.

Both these examples highlight the shortcomings of administrative reallocation decisions and the problems associated with inadequate water property right and institutional structures. Given that water reallocation mechanisms based on direct administrative intervention rarely lead to economically efficient outcomes, it is likely there are economic benefits to more-formal market structures. Further, by their nature, more-formal market structures will provide the mechanism to transparently reallocate water and resolve disputes using legal institutions. The next section discusses the modelling framework used to estimate the benefits of water reallocation in agriculture.

Estimating the benefits of water reallocation in the Yellow River Basin

Model specification

The methodology used to model water reallocation in the Yellow River Basin involved four steps. First, a flexible production function was estimated to characterise the agricultural production technologies in the basin for each region and for seven agricultural crops: wheat, maize, rice, vegetables, cotton, soybean and potatoes. Second, a non-linear profit maximisation problem was formulated for each region. The objective function embeds the flexible crop production functions and input costs. The constraints reflect regional resource limits on the availability of land and water, as well as any policy restrictions. Third, the optimisation model was solved over a range of water prices to estimate the parameters of a regional water demand function. Fourth, these water demand functions were incorporated into a spatial equilibrium model of regional water markets for the Yellow River Basin to estimate the potential gains from water transfers within the basin.

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This methodology was chosen because data sources were limited and the majority of the data that were available are cross-sectional. Production and cost parameters are derived from empirical data. The second stage is to determine the resource costs of land and water, or any policy constraints as these costs are not fully reflected in input prices. These are derived by calibrating the optimisation to recreate the base-year production and resource-use data. The end result of this zero degree of freedom approach is the development of a positive rather than a normative model that can be used to evaluate policies designed to reallocate resources through trade or administrative means.

Regions

For the purpose of this study, the Yellow River Basin was divided into 10 regions based on hydrologic, agroclimatic, and soil conditions. This is consistent with previous work undertaken by the World Bank (World Bank 1993). The important administrative boundaries and provinces included in each region are provided in Table 2 and shown in Figure 1. There are three basic principles underlying this classification: first, within regions, natural geographic conditions, water resource development and use, and water conservancy development and objectives are sufficiently similar or sufficiently dissimilar; second, distinctions important to different main-stem river sections or tributaries are maintained; third, if possible, the administrative boundaries and catchment areas corresponding to major works on the main stem or tributaries are preserved.

Estimating parameters of crop production and implicit land cost functions

Assembling a minimum dataset

The data for the research come from both field surveys and secondary sources. The results of two large survey activities are included in the field survey data. The first survey, the China Water Management Survey (CWMS), was conducted in 80 villages in Ningxia, Henan and Hebei provinces in 2001 and 2004. A second survey in 2004, the North China Water Resource Survey (NCWRS), collected data from village leaders and accountants from more than 400 villages in Inner Mongolia, Hebei, Henan, Liaoning, Shaanxi and Shanxi provinces. The methodology used was an extended version of the community-scale village instrument of the CWMS survey. The sample was chosen using a stratified random sampling strategy for the purpose of generating a sample repre-

sentative of northern China. The secondary sources include production-cost data at provincial level, and areas and yield of crops at county level collected by the Ministry of Agriculture.

Table 2. Regions of the Yellow River Basin

Region	Provinces included in each region
1	Sichuan (3), Gansu (1), Qinghai (11)
2	Gansu (23), Qinghai (16)
3A	Gansu (7), Ningxia (16), Shaanxi (1)
3B	Inner Mongolia (28)
4	Shanxi (21), Inner Mongolia (2), Shaanxi (10)
5A	Shanxi (50), Henan (6)
5B	Gansu (23) Ningxia (4), Shaanxi (68)
6	Shanxi (6) Shaanxi (1), Henan (20)
7A	Henan (37)
7B	Shandong (65)

Note: In column 2, the figures in brackets are the numbers of provincial counties that should included be in the region.
Source: Authors' calculation based on county-level data provided by the Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences.

The parameters of production technology and regional resource use were estimated from a dataset for the base year, 2002. The dataset combined county-level agricultural statistics with village and farm-level survey data. The assembled database included land area allocated, water use, labour and material inputs, product and input prices, and average yield for each region and crop. Water use was estimated by multiplying the area allocated by the long-term average of total crop evaporative requirement of water, estimated using Penman evaporation data, crop coefficients and the number of days of a year the crop occupies the land. Summing the land area allocated and the volume of water used over all crops gives an approximation of the regional land and water endowments that can be allocated between crop enterprises.

The minimum dataset to estimate the parameters of flexible crop production functions and true costs also required, for each region, the scarcity or rental value of allocable land and water resources. As there are no market price data for land or water, a method suggested by Howitt (1995) was used and the resource scarcity values were estimated by fitting a linear program model for available data. These scarcity values are treated as implicit market prices. In each regional linear program model, profits from regional crop production are maximised subject to resource constraints levels, as estimated above, and a set of calibration constraints

designed to exactly calibrate to base-year land allocations. Depending on the relative endowment of land and water in the region, one of the two resources becomes scarcest with a positive scarcity value. The dual values or the shadow prices of the resource constraints of the linear program models are taken as their scarcity values.

Crop production functions

The specification of production technology that was used is more flexible than the commonly used fixed-coefficient Leontief specification. This is preferred because the Leontief specification may produce misleading results from the impacts of policy changes. For each crop, the production technology is assumed to exhibit constant elasticity of substitution (CES) between inputs. For each region and crop, a CES production function of the form given in (1) is to be estimated.

$$y_{ri} = \alpha_{ri} \left(\sum_j \beta_{rij} x_{rij}^{\gamma} \right)^{\frac{1}{\gamma}} \quad (1)$$

where $\gamma = (\sigma - 1)/\sigma$

σ = elasticity of substitution

β_{rij} = share of input j in the production of crop i in region r, with $\sum_j \beta_{rij} = 1$

α_{ri} = scale parameter for crop i, in region r.

For each region, r and crop i, production function (1) which uses j inputs has j unknown parameters ($j - 1$ share parameters of β_{rij} and α_{ri}). Just as in the case of calibration of computable general equilibrium (CGE) models, for each input j, the share parameter β_{rij} is estimated using data on the use and unit cost of all individual inputs (Howitt 1995). The unit factor cost used here includes scarcity value estimated as explained above, on top of the nominal cost. In the case of land, the unit factor cost also includes a marginal crop-specific cost derived from the shadow price of calibration constraints to reflect the heterogeneity in land allocated to different crops. The unit factor costs used here represent true costs that exactly exhaust total revenue for each crop and thus ensure the model exactly calibrates to base-year land allocation to alternative crops (Howitt 1995). For each region, r and crop i, the remaining parameter, α_{ri}, is estimated by inverting equation 1 and then substituting estimated values of β_{rij} and base year y_{ri} and x_{rij} values.

Implicit land cost functions

As the estimated share parameters, β_{rij}, include marginal crop-specific costs due to land heterogeneity, the parameters of the corresponding total land cost function should also be derived. This cost function accounts for an implicit cost that needs to be explicitly incorporated to exactly calibrate to base-year land allocation data. For each region, r, and crop, i, the implicit cost, c_{ri}, is given by a quadratic function of the area allocated to that crop

$$c_{ri} = \delta_{ri} x^2_{ri, j=land}$$

and thus the marginal cost by

$$\partial c_{ri} / \partial x_{ri, j=land} = 2\partial_{ri} x_{ri, j=land}$$

The parameters δ_{ri} are estimated by substituting the shadow prices of linear programming calibration constraints for the LHS and the base year land allocation for $x_{ri, j=land}$ on the RHS of the latter (marginal land cost) expression.

Regional agricultural production problem

It is assumed that in each region, scarce land and water resources are allocated to alternative cropping enterprises to maximise aggregate profits. The corresponding profit maximisation problem is given in equations (2)–(4).

$$\text{Maximize} \sum_i p_{ri} y_{ri} - \sum_{i,j} \omega_{rij} x_{rij} - \sum_i \delta_{ri} x^2_{ri, j=land} \quad (2)$$

subject to

$$y_{ri} = \alpha_{ri} \left(\sum_j \beta_{rij} x_{rij}^{\gamma} \right)^{\frac{1}{\gamma}}, \text{ and} \quad (3)$$

$$\sum_i x_{rij} \leq \psi_{rj} \quad (4)$$

where p_{ri} = price of product of crop i in region r (Yuan/t)

ω_{rij} = nominal price of input j used in crop i in region r (Yuan/'000 m³ for water and Yuan/day for labour)

ψ_{rj} = endowment of resource j in region r (ML for water, days for labour and ha for land).

For each region, r, the production problem is to maximise the aggregate profit from crop production (1) subject to a CES production technology for each crop (3) and regional resource constraints (4) which state, for each input, j, its use by all crops cannot exceed the endowment, ψ_{rj}.

This model is specified and solved in GAMS (general algebraic modelling system), a modelling framework for mathematical programing and optimisation,

as a non-linear programing problem. For further information on GAMS, see <www.gams.com>.

Estimation of water demand elasticities

For each region, the model given in equations (2)–(4) is run to estimate regional demand for water at 50 discrete scarcity values (or prices) of water, $\omega_{r,j\,=\,water}$, ranging from 0 to 300 Yuan/ML. For each region, the dataset with 50 observations of water price and quantity demanded is used to estimate the elasticity of demand assuming a constant elasticity specification. The base-year water demand, water scarcity value and the estimated elasticities are given in Table 3. The derived market prices or water scarcity values differ substantially between regions and suggest that there can be significant gains from reallocating water between regions.

Table 3. Water use and price and estimated elasticities by region, 2002

Region	Base-year water use (million m^3)	Scarcity value of water[a] (Yuan/ML)[b]	Demand elasticity
1	18	6	−0.76
2	1,129	6	−0.78
3A	3,794	16	−0.87
3B	1,786	19	−0.88
4	735	16	−0.84
5A	4,347	50	−1.13
5B	9,241	189	−1.81
6	3,249	120	−0.85
7A	8,304	133	−0.88
7B	15,908	103	−0.89

[a] Estimated as the net agricultural return of an additional 1000 m^3 of water use in the region less delivery charges.
[b] 1000 m^3 = 1 megalitre (ML).

Regional water market model

For each region, r, water use, d_r, is a declining function of the user price, p_r. Assuming a constant elasticity specification, the demand function can be given as $d_r = \phi_r p_r^{\eta_r}$, where: ϕ_r is the scale parameter and η_r is the elasticity of demand. For each region, the value of scale parameter, ϕ_r is estimated by substituting the estimated demand elasticity and the base-year water use and price given in Table 1. For each region, water supply is assumed to be equal to base-year water use. The relatively high scarcity value of water (or implicit price) in region 5B is due, in part, to it drawing the majority of water used for irrigation from the Wei River. This region cannot be an importer of water after the reallocation, as it is not

possible to substitute Wei River water for Yellow River water for environmental reasons. It can, however, be an exporter of water.

Inter-regional water trade

Inter-regional trade can be shown graphically in a back-to-back diagram. Figure 2 illustrates price–quantity combinations before and after trade and measures of welfare changes for the case of two regions.
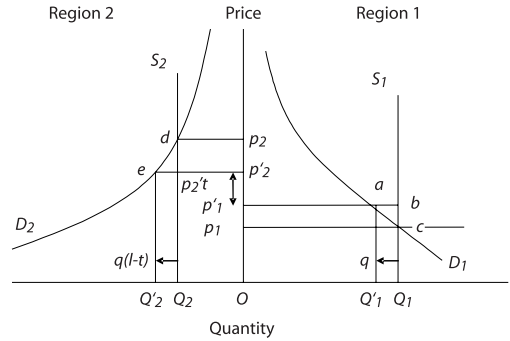

Figure 2. Water trade between two regions: price–quantity combinations before and after trade and measures of welfare changes

Demand and supply schedules are denoted by D and S and quantity and price by Q and p. Subscripts 1 and 2 are used to denote the region. Price quantity combinations for region 1 and 2, before trade are given by (Q_1, p_1) and (Q_2, p_2) and after trade by (Q'_1, p'_1) and (Q'_2, p'_2). The unit cost of transport losses of water between the two regions is given by p'_2t. When trade between the two regions is allowed, region 1 sells q volume of water to region 2 that receives $q(1 - t)$ after netting out the transport losses.

Water users in region 1 lose consumer surplus measured by the trapezoidal area $p_1p'_1ac$ while they gain from sales of water measured by the rectangle Q'_1abQ_1. The gains from trade for region 1 are thus given by Q'_1abQ_1 less $p_1p'_1ac$. Water users in region 2 gain consumer surplus measured by the trapezoidal area $p_2p'_2ed$. Total net gain from trade is given by $p_2p'_2ed$ plus Q'_1abQ_1 less $p_1p'_1ac$. If water is transferred administratively rather than traded through the market, assuming the same price and quantity combinations given in Figure 1, the area Q'_1abQ_1 represents a fair compensation payment for region 1 water users.

Trade flows

Trade flows

See equation (5) at the foot of this page. For each region, *s*, regional water use plus water exported to downstream regions, q_{sr}, cannot exceed the regional water supply, *s*, plus water imported from upstream regions, q_{rs}. If the regional water use plus water exports is less than the supply plus imports from other regions after adjusting for transport losses, then the price of water is zero and if the price is positive then the first expression is satisfied with strict equality.

Price arbitrage conditions

$$p_r \geq p_s(1-t), \; q_{rs}[p_r - p_s(1-t_{rs})] = 0, \text{ for } r = 1,....,10$$

At each region *r*, there is a common price or scarcity value of water traded from the region to the adjacent downstream region, p_r, that cannot be lower than the price of water in the adjacent downstream region net of the cost of transport losses involved in transferring water to it. If the price in region *r* exceeds the price in the downstream region *s* net of the cost of transport losses, then there are no sales of water to the downstream region. If water trade between the two adjacent regions is positive, then the price in these two regions differs only by the cost of transport losses between them.

This model is also specified and solved in GAMS but as a mixed complementarity problem (MCP).

Effects of water reallocation in the Yellow River Basin

The total value of agricultural production in the Yellow River Basin is estimated to be around 57 billion Yuan. Total cultivated land in the Yellow River Basin is almost 16 million ha (Table 4). Across the 10 regions, cultivated land ranges from more than 3 million ha (such as regions 5B and 7B) to less than 1 million ha (such as region 1). The share of irrigated land varies considerably between regions, with those in the lower reaches having the highest proportion of irrigated land. For example, in region 7A (Henan Province), more than 80% of cultivated land is irrigated. In contrast, only 4% of cultivated land is irrigated in region 1, in the upper reaches, and only 11% in region 4, in the middle reaches. This is because irrigators in the downstream reaches have access to groundwater that is used conjunctively with surface water resources. Irrigation in upper and middle reaches depend mainly on surface water.

Land-use intensity and cropping structures in these regions are also highly varied. Due to various irrigation conditions and other factors, land use intensity in downstream reaches also is higher than that in the upper and middle stream reaches (Table 3). For example, the multiple cropping index in region 7A is near 2, while it is less than 1 in region 1.

The optimal reallocation of irrigation water was estimated by simulating trade between regions. With trade, the scarcity value of water is equated across regions, allowing for differential conveyance losses.

After the trade, water is reallocated from upstream to downstream and from low to higher returning uses, leading to an overall increase in irrigated agricultural production. Under an optimal reallocation in the Yellow River Basin, a large volume of water would be imported into regions 6 and 7A and, to a lesser extent, region 7B (Figure 3). This water is used for rice, cotton, maize and wheat production after the trade. The increase in rice and wheat production in the importing areas more than offsets the reductions in wheat production in the exporting areas, and overall production in the basin rises.

The water is exported mainly from regions 3A and 5A, and to a lesser extent, from regions 2, 3B and 4 where the scarcity value of water is low relative to downstream regions. That is, downstream users are willing to pay a price greater than the use value in upstream regions, creating profitable trading opportunities. Much of the imported water is used for wheat and rice production, the same crops that are forgone in all water exporting regions. However, the productivity of these crops in the importing region is higher. In addition, maize production in importing regions is increased as it is a high-value crop used as animal feedstock.

Production of maize, cotton, potatoes and rice in importing regions increases, provided there is more land and labour available to make use of the imported water. Total cultivated area increases by 30% each in regions 6 and 7A, and by 22% in 7B, assuming that more labour will be available in these regions. Similarly, less labour will be required by exporting regions.

$$\phi_s p_s^{\eta_s} + \sum_r q_{sr} \leq s_s + \sum_r q_{rs}(1 - t_{rs}), \; p_s \left[\sum_r q_{sr} - s_s + \sum_r q_{rs}(1 - t_{rs}) \right] = 0, \text{ for } s = 1,....,10 \tag{5}$$

The trade equalises the scarcity value of water across all regions in the basin, except region 5B. After the trade, the price of water increases significantly in the upstream exporting regions, mainly 5A and 3A, and decreases in the downstream importing regions, regions 6, 7A and 7B.
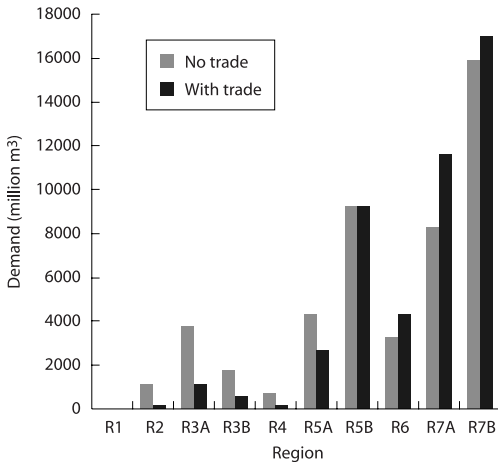

Figure 3. Water demand in regions of the Yellow River Basin

There is an estimated welfare gain of almost 1.3 billion Yuan per year in the importing regions after the water reallocation (Table 5). These benefits accrue as a result of significant increases in crop pro-

duction in the importing regions. This is partially offset by reductions in agricultural production in the exporting regions of around 277 million Yuan per year. The total benefit of water reallocation, comprising the increase in the value of agricultural production, is around 1 billion Yuan per year. This represents an increase in the value of agricultural production of around 1.8 per cent.

The benefits that are generated as a result of water sales accrue to the holders of the property rights in the exporting regions. If, as is the case now, irrigators or irrigation districts do not own the water, the benefits of the water sales would go to the state. This would result in a loss in potential income from the sale of water to irrigators in the exporting regions of more than 500 million Yuan per year. That is, irrigators in the exporting regions would be more than 500 million Yuan worse off each year after the reallocation as they do not currently hold the property rights to the reallocated water. Alternatively, this is the amount that they would need to be compensated for the loss of access to water resources if the water was administratively reallocated. This is in addition to the reduction in agricultural production valued at around 277 million Yuan per year.

The impact of water reallocation on farm household incomes is presented in Table 6. If exporting regions are not compensated for the reallocated water, reductions in farm household income are greatest in the middle reaches of the basin — regions 5A, 3A and 4 – which have the greatest reductions in

Table 4. Cultivated land, share of irrigated land, sown area, multiple cropping index and farm household income in the ten regions of the Yellow River Basin, 2002

Region	Cultivated land ('000 ha)	Share of irrigated land (%)	Total sown area ('000 ha)	Multiple cropping index[a]	Farm household income (Yuan/year)
1	79	4	59	0.75	1682
2	913	26	1034	1.13	1440
3A	1246	39	1350	1.08	1776
3B	1910	51	1185	0.62	2419
4	1315	11	1069	0.81	2341
5A	1735	40	1773	1.02	2903
5B	3160	34	4061	1.29	1521
6	848	44	1277	1.51	2189
7A	1411	82	2659	1.89	2178
7B	3102	63	5370	1.73	2759

[a] Multiple cropping index is the ratio of sown area over cultivated area.
Source: Authors' calculations based on county-level data provided by the Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences.

agricultural production. Conversely, with compensation, all regions benefit from the reallocation, with the largest benefits going to some regions that have the lowest farm household income in the basin, such as regions 2 and 3A. The increase in farm household income in the importing regions is considerably lower if farmers hold water property rights as they would need to pay for the water they received (in addition to delivery charges), reducing the benefits of water reallocation in that region.

Concluding remarks

Preliminary findings from the modelling work presented here suggest that there would be considerable gains from water reallocation. In the scenario presented, water moved downstream to higher value agricultural use under conditions of free trade. The economic benefit, in terms of the increased value of agricultural production, was around 1 billion Yuan per year. If farmers in water-exporting regions had the property rights to transferred water, income from water sales would more than offset the forgone income from reduced agricultural production. The income from water sales is estimated to be around 500 million Yuan per year. In the absence of property rights, the lost value of agricultural production lowers farm household incomes substantially. Conversely, with revenue from the sale of water, farm household incomes in the exporting regions would

rise substantially. Importantly, without compensation, the regions with the lowest incomes are likely to be affected the most by water transfers.

Water can be reallocated using by a number of means, two of which have been considered here — administrative reallocation and free water trade. While it may be theoretically possible to reach an economically efficient outcome by administering water reallocation, there are number of barriers that prevent this from happening in practice. For example, the information requirements are demanding. Information asymmetry between the administrative body and irrigators on the marginal value and opportunity costs of water mean that allocation decisions would be made based on imperfect information about where the greatest benefits can be generated.

Water markets, on the other hand, coordinate price signals and disperse information and preferences. Water markets would provide a mechanism to transfer water to higher-value uses on a large scale and to the other productive uses, such as industry, and the environment. For formal water markets to work efficiently, property rights to water must be private, exclusive and transferable. Secure ownership provides the incentive to invest in human or physical capital to improve the productivity of the resource. Transferability provides the flexibility to reallocate the rights according the changing demand and other conditions. The role of the state is to protect these

Table 5. Benefits of water reallocation in the Yellow River Basin (million Yuan)

	Water-importing regions	Water-exporting regions	Basin wide
Change in value of agricultural production	1335	–277	1058
Value of the water transferred	–498	498	0
Total benefit of reallocation[a]	837	221	1058

[a] Include benefits of water sales accruing to irrigators in the exporting regions. For those farms that sold water, farm income after reallocation also includes the annual lease value of water sold or the annualised value of the compensation received if the water was transferred administratively.

Table 6. Impact of water reallocation on farm incomes (Yuan/farm) in different regions of the Yellow River Basin

Region	1	2	3A	3B	4	5A	5B	6	7A	7B
Before reallocation	1682	1440	1776	2419	2341	2903	1521	2189	2178	2759
Change in farm household income without property rights	–59	–20	–64	–49	–58	–46	0	176	183	27
Change in farm household income with property rights[a]	105	40	57	38	54	19	0	113	118	15

[a] For those farms that sold water, farm income after reallocation also includes the annual lease value of water sold or the annualised value of the compensation received if the water was transferred administratively.

property rights by enforcing contracts and reducing transactions costs and other barriers to exchange. However, legislation, institutions and the necessary regulatory framework to support water reallocation do not currently exist in the Yellow River Basin.

While the issues facing resource managers in China are unique in many ways, establishing and implementing water property rights structures to facilitate reallocation has been undertaken in many developed and developing countries. A body of literature exists drawing lessons from experience in these countries and assessing its relevance in others. Hu (1999), for example, explored the relevance of the Australian experience in the Murray–Darling Basin to the Chinese context and concluded a similar legal and institutional framework would not be suitable because of the existing administrative framework in China and the incomplete and uncertain specification of resource access. Perhaps the most pervasive of reasons, however, is the small scale of farming in China and the consequent transactions costs of implementing water property rights at that scale. If, on the other hand, water rights are granted at a higher level — for example, at the irrigation district level — there may not be sufficient incentive for farmers to engage in water-saving practices unless they are adequately compensated.

Acknowledgments

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The potential use of FILTER technology for treatment and reuse of wastewater in China

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Abstract

In an ACIAR research project, the potential use of FILTER (**f**iltration and **i**rrigated cropping for **l**and **t**reatment and **e**ffluent **r**euse) technology developed in Australia is being evaluated for overcoming the problems of wastewater treatment and reuse in China. The FILTER technique combines the use of nutrient-rich effluent for cropping, with filtration through the soil to a subsurface drainage system during periods of low cropping activity and high rainfall. FILTER field trials in Australia showed that the system could be operated to ensure that the subsurface drainage water has pollutant concentrations that meet environmental authority criteria for potential discharge to natural water bodies. Use of the FILTER system on a saline–sodic soil to treat saline sewage effluent led to continuing high crop yields and progressive reduction in salinity and sodicity of the soil, by maintaining an adequate leaching fraction.

FILTER trials in China were conducted at Wuqing, located 65 km southwest of Tianjin City. At this site, FILTER plots measuring 60 m x 40 m were used. During four cropping seasons there were reductions of 97–99% and 83–87%, respectively, in total-nitrogen and total-phosphorus loads in the drainage waters. The loads of suspended solids, BOD and COD were markedly reduced also, by 68–81%, 61–79% and 75–86%, respectively. A pesticide–spiking experiment on the FILTER plots showed complete removal of malathion in the drainage waters and, in the case of chlorpyrifos, the load reduction was 99.8%. In a heavy metal spiking trial using cadmium, copper, mercury and lead, there was a 96% reduction in the concentration of the heavy metals in the drainage water, indicating their strong absorption by the soil. The heavy metal load reduction exceeded 99%. Overall, the results indicate that the silty clay soils at the trial site have good pollutant removal and retention properties.

The field trials in both China and Australia indicate that the FILTER system offers opportunities for sustainable irrigated cropping with saline wastewater on degraded salinised lands. It is also capable of removing the major pollutants in wastewaters such as nutrients, BOD, COD, total suspended solids, *E. coli* and agricultural chemicals that adsorb onto the soil during filtration, thereby increasing the potential reuse of the drainage water for downstream irrigation and other uses. The pollutant load reduction rates were comparable at the two sites at Griffith and Wuqing with clay and silty clay soils, respectively.

FILTER field trials have also been installed in Da Tong in Shanxi Province to evaluate its potential, as well as design and management requirements at a site with permeable soils, deeper water tables and very cold weather conditions. Early indications are that the harsh winters in Shanxi are not easily managed by simple modifications to the FILTER approach. Combining FILTER with controlled environment poly-greenhouses is being investigated to try to overcome the winter wastewater renovation problems.

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FILTER技术在中国污水处理和再利用中的应用潜力

摘要：在一个ACIAR研究项目中，评价了在澳大利亚开发的FILTER（filtration and irrigated cropping for land treatment and effluent reuse）技术应用潜力，以解决中国在污水处理和再利用中问题。FILTER技术将富营养污水被作物利用和在作物利用淡季及雨季通过土壤过虑后汇集到地下排水系统的技术相互结合起来。FILTER 在澳大利亚的田间试验表明，这个系统的运行可以保证从地下排水系统排出的水中的污染物含量可以满足环保部门确定的标准，从而可以排放到自然水体当中。在盐碱地上应用FILTER 系统处理含盐的生活污水还可以保证作物高产，且通过维持足够的排放比例可使土壤中的盐碱含量逐步减少。在中国FILTER试验在天津市武清县开展。在这个试验点上FILTER的面积为60 m x 40 m。在4个种植季节中处理后排出水中总氮和总磷的含量比引入的污水分布减少97-99% 和 83-87%。悬浮物、BOD 和 COD 也有显著减少，分别减少68-81%, 61-79% 和 75-86%。在FILTER上应用杀虫剂试验表明，FILTER可以在排水中完全去除malathion，对chlorpyrifos的去除率为99.8%。在去除重金属试验中用了镉、铜、水银和铅，排出的水中重金属含量减少96%，表明土壤对重金属有很强的吸附功能。重金属浓度降低量超过99%。总体上来讲，试验表明试验地上的沉积粘土具有很好的污染物去除和吸纳特性。在中国和澳大利亚的试验表明，在退化的盐碱地上FILTER系统可以实现用含盐污水持续灌溉作物。它还可以去除污水中的主要污染物，如营养物、BOD、 COD、总悬浮物、 E. coli和在过虑过程中吸附到土壤中的农业化学物质，因而可以使排放出的水在下游可用于灌溉和其他用途。在澳大利亚Griffith试验点上土壤为粘土和在天津武清县试验点土壤为沉积粘土，这两处试验对污染物的去除效果是相当的。

在山西的大同市也建立了FILTER 试验系统，目的是评估该系统在透水性强、地下水埋深大和寒冷的应用潜力，并研究相应的设计和运行管理需求。初步试验表明，在山西寒冷的冬天难以通过简单地修改FILTER使其易于被运行管理。正在研究将FILTER和塑料大棚控制的环境相结合来克服在冬季处理污水的问题。

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Introduction

Environmental protection agencies (EPAs) in many countries have promoted land treatment and reuse of sewage effluent and other wastewaters to reduce pollution of natural water bodies. When soil conditions are suitable, land treatment of wastewater for irrigated cropping or forestry systems can be successfully practised. However, on soils with restricted drainage and high watertables, effluent irrigation can lead to waterlogging as well as salinisation and sodification, where the leaching fraction required to remove excess salts in wastewater is inadequate. This could reduce crop yields and nutrient removal, and hence the long-term sustainability of such sites. In addition, where the wastewater needs to be stored on expensive semi-urban lands during wet weather and winter periods, when the evapotranspiration needs for irrigated cropping falls, the costs escalate. Therefore, alternative land application technology has to be developed for such marginal application sites on urban lands.

The land FILTER technique

The land FILTER (**f**iltration and **i**rrigated cropping for **l**and **t**reatment and **e**ffluent **r**euse) technique was proposed to overcome the aforementioned problems, and to provide a sustainable and cost-effective land-treatment system on the limited available areas of high-value land around urban centres (Jayawardane 1995). The FILTER technique combines using nutrient-rich effluent to grow crops, with filtration through the soil to a subsurface drainage system during periods of low cropping activity and heavy rainfall (Figure 1). It thus provides wastewater treatment throughout the year and the use of high hydraulic loading rates on the small areas of available land, with reuse or discharge of the subsurface drainage waters.

In the FILTER system, the rate of wastewater application and subsurface drainage could be designed to ensure adequate pollutant removal, thereby producing low-pollutant subsurface drainage
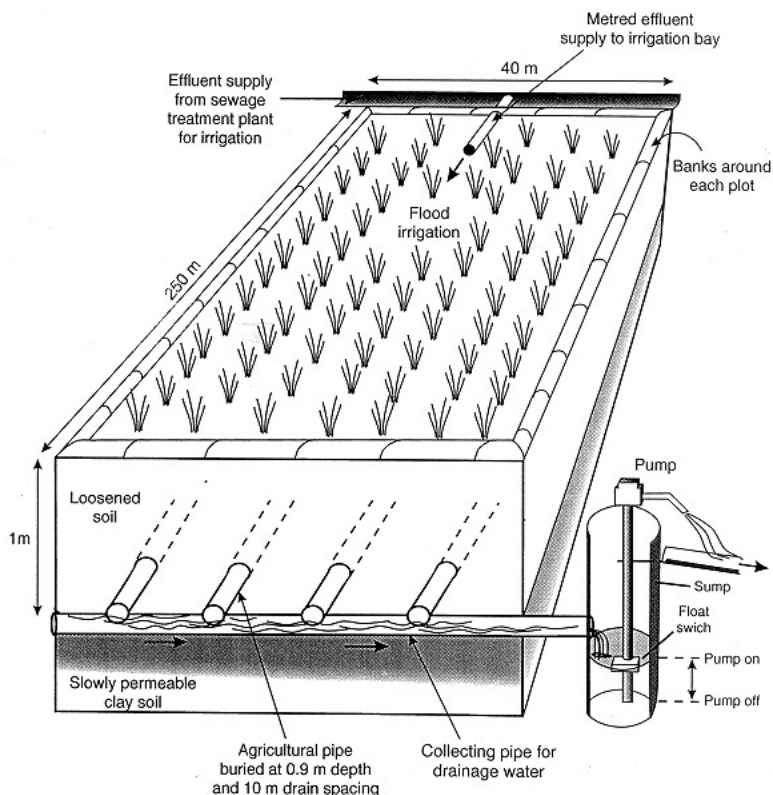

Figure 1. Schematic diagram of FILTER plots

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water that meets EPA criteria for discharge to surface waterbodies or for other urban reuses. This filtration phase could be followed, if and when necessary, by a cropping phase to remove any nutrients stored in the soil of FILTER plots, thereby maintaining a sustainable system. The preliminary experiments at the Griffith, New South Wales FILTER trial site in Australia showed that adequate crop growth and nutrient removal could be achieved by crops grown during the filtration phase, which eliminated the need for a separate cropping phase (Jayawardane et al. 1997a,b).

In the FILTER system, the land at the effluent application site is prepared as follows. In soils with low permeability, physical loosening and chemical amelioration of the soil to about 1 m depth is used to increase soil macroporosity and hydraulic conductivity. A network of subsurface drains is installed at the bottom of this loosened layer, with control valves to allow for the regulation of leaching rates through the soil. Alternatively, controlled pumping from a drainage sump could be used to regulate the outflow, to approximately match the net hydraulic loading of the system. The controlled drainage system enables manipulation of the watertable, and hence provides control of the depths of the aerated and anoxic soil layers above the drains, to maximise the pollutant removal and to provide adequate root-zone conditions for crop production.

A commercial FILTER system requires installation of 7–10 FILTER blocks. In operating the system, the wastewater is applied to each block on a 10–14 day rotation. Each effluent application cycle or filter event (Figure 2) consists of four consecutive stages. These four stages are: wastewater application (irrigation); followed by a post-irrigation equilibration period; a pumping period (until drainage outflow approximately matches the net inflow); and finally a no-pumping equilibration period (leading to flattening of the watertable). The subsurface drains are closed except during the pumping period, to maximise the wastewater interaction with the soil. The manipulation of these four-stage effluent application and drainage operations could be used to maximise the removal of nutrients and other pollutants, as the wastewater flows through the soil. Crop uptake and microbial degradation processes could be used to prevent the long-term excessive build-up of pollutants in the soil. The FILTER design and management at a given site depend on factors such as the land area available, the pollutants present in the wastewater,

the daily wastewater production rate and the requirements for pollution reduction by the local EPAs.
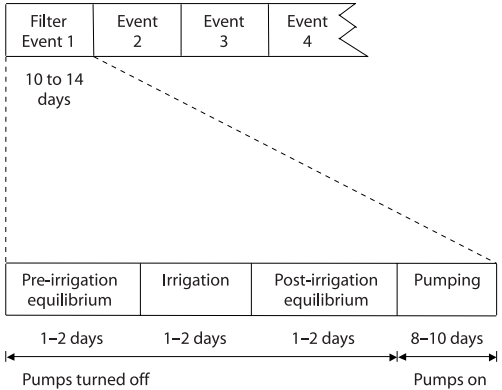

Figure 2. FILTER irrigation and drainage operations, during a filter event

Field testing of the FILTER system in Australia and China

Preliminary testing of the FILTER technique was carried out at the Griffith Sewage Works site in central New South Wales, Australia, on eight 1 ha preliminary experimental plots (Jayawardane et al. 1997a,b), and on a 15 ha pilot trial (Biswas et al. 1999a,b; Jayawardane et al. 1999, 2001a) on a highly salinised, heavy clay soil with impeded drainage and a high watertable. The results obtained during the Griffith preliminary trials and pilot trial showed that the FILTER system meets its primary objectives of providing pollutant concentration reductions to below EPA limits in drainage waters, while maintaining adequate drainage flow rates and crop production. For instance, during the five cropping seasons on the pilot trial, the total phosphorus in the effluent applied varied between 2.0 and 8.2 mg/L, while the mean value in the drainage waters was 0.31 mg/L (Figure 3). The total-nitrogen concentration in the effluent applied ranged from 4.6 to 33.1. The total-nitrogen concentrations in the drainage waters were initially high due to leaching of pre-FILTER soil accumulations of nitrogen, but fell below 11 mg/L after filter event 5 of the first cropping season, and remained below this value for the next four cropping seasons. Concentrations of sus-

pended solids, BOD$_5$ and chlorophyll *a* were also markedly reduced in the drainage waters.
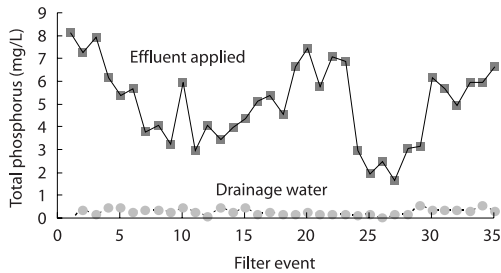

Figure 3. The mean total-phosphorus concentrations in the sewage effluent applied and subsurface drainage discharges from the pilot FILTER trial, during successive filter events over five cropping season

Pollution load reductions in the drainage waters (Table 1) during the five cropping seasons of the pilot trial for total P, total N, suspended solids, BOD$_5$, chlorophyll *a*, and oil and grease were 96, 60, 81, 93, 100 and 60%, respectively (Jayawardane et al. 1999, 2001a).

Soil chemical analysis at the Griffith trial site showed that the pre-FILTER nutrient accumulations which occurred due to previous effluent irrigations were depleted by intensive cropping under the FILTER system. Soil analysis also indicated a reduction in the pre-FILTER levels of soil salinisation (Figure 4) and sodification after installation of the FILTER system, through removal of excess salt in the subsurface drainage (Jayawardane et al. 2001a,b; 2002a). The FILTER system could thus be used to ameliorate degraded salinised and waterlogged land, thereby adding economic value to the reclaimed lands. This is in contrast to wastewater irrigation schemes where good quality and high-value agricultural lands with adequate drainage are required to provide a sustainable system. Substantial crop yields were obtained on FILTER plots. These could be used to offset costs of installation and operation of commercial FILTER systems.
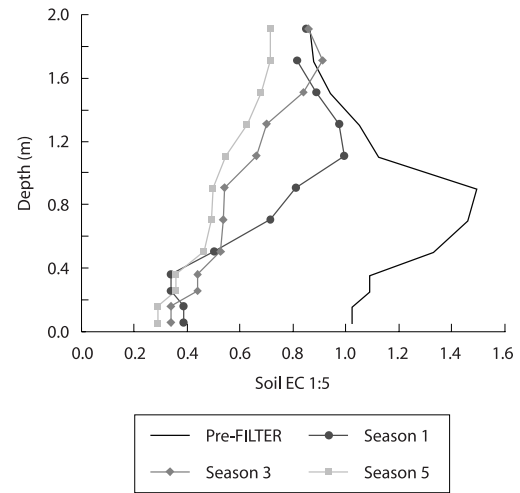

Figure 4. Soil salinity reductions during operation of the pilot FILTER trial

Table 1. Pollutant load reductions (%) during the Griffith preliminary and pilot FILTER trials, and in the Wuqing FILTER trial (with drain spacings of 5 m and 10 m)

Pollutant	Griffith preliminary	Griffith pilot	Wuqing (5 m drains)	Wuqing (10 m drains)
Total P	96	96	99	99
Total N	75	60	82	86
Suspended solids		81	68	81
BOD$_5$		93	61	79
COD			75	86
Grease and oil		60		
Chlorophyll *a*		100		
Malathion	99.4			100
Chlorpyrifos	100			99.8
Other pesticides	98–100			
E. coli (counts)		100		

Spiking trials with the full range of pesticides used in the Murrumbidgee Irrigation Area (bensulfuron, molinate, malathion, chlorpyrifos, diuron, bromacil, atrazine, metolachlor and endosulfan) showed that FILTER systems could be used to reduce the pesticide concentrations from excessively high levels observed in surface drains of the area to values well below EPA limits (Jayawardane et al. 1997a; Biswas et al. 2000a,b). The pesticide loads were reduced by more than 98%.

Wastewater pollution surveys in China indicate severe pollution problems in many rivers, lakes, bays, groundwater and coastal waters. Recognising the need to develop and evaluate economically and socially acceptable methods of treating and reusing wastewater to increase crop production and minimise pollution of waterbodies in China, the China Institute of Water Resources and Hydropower Research (IWHR), Tianjin Water Conservancy Scientific Research Institute (TWCSRI) and CSIRO Australia carried out an ACIAR research project on the FILTER system for land treatment of wastewaters. The research was carried out at a field site in Wuqing county near Tianjin, China. The field site is located in an area where there is intense competition for scarce freshwater resources among users and extensive pollution of waterbodies from wastewater discharges. The area also has saline wastewaters and extensive areas of agricultural lands with saline soils and high watertables, which could potentially be ameliorated for cropping by the FILTER technique, thereby providing a dual benefit. The area surrounding the field trial site receives irrigation diverted from Beijing City 'sewage river', which also collects untreated sewage effluent discharge from a nearby township.

FILTER trials in China were conducted at Wuqing, located 65 km south-west of Tianjin City. The main aim of the Wuqing trial was to evaluate the FILTER techniques for sustainable crop production and for removing pollutants in wastewater (Gao et al. 2000). At this site, FILTER plots measuring 60 m × 40 m were used (Figure 5). During four cropping seasons there were reductions of 97–99% and 83–87%, respectively, in total-nitrogen and total-phosphorus loads in the drainage waters. The loads of suspended solids, BOD and COD were also markedly reduced, by 68–81%, 61–79% and 75–86%, respectively. A pesticide-spiking experiment on the FILTER plots showed complete removal of malathion in the drainage waters and, in the case of chlorpyrifos, the load reduction was 99.8%. In a heavy-metal spiking trial using cadmium, copper, mercury and lead, there was a 96% reduction in concentration of the heavy metals in the drainage water, indicating a strong adsorption of the heavy metals in the soil. The heavy metal load reduction exceeded 99%. Overall, the results indicate that the silty clay soils at the trial site have good pollutant removal and retention properties. The results indicate pollutant reduction rates comparable to those observed in the Australian field trials on a clay soil (Table 1), while maintaining adequate flow rates and crop production. The FILTER site at Wuqing was also used to treat wastewater from a nitrogen fertiliser factory that was known to be polluting a river near Tianjin. The FILTER system markedly reduced the pollutants in the wastewater, and the yield of crops grown increased due to the nitrogen additions in the wastewater.

Figure 5. FILTER trial site in Wuqing, China. The subsurface drainage from the FILTER plots located on both sides of the centre road collects in the drainage sumps (located in a row adjacent to the road) and is then pumped to the drainage storage tank (right foreground)

Collaborative research between the Australian and Chinese scientists was also carried out on developing FILTER operational systems and models to provide improved understanding and management of FILTER systems to treat different wastewater (Jayawardane et al. 2002b,c; Cheng et al. 2003). Collaborative studies were also conducted on optimisation modelling, to assist wastewater managers in optimising the FILTER design and management according to the needs for pollutant removal and wastewater reuse at specific sites (Gao et al. 2002).

Current FILTER trials in Shanxi Province, China

The main aim of the new field trial at Shanxi is to develop a holistic, integrated system for using wastewater in a sustainable irrigated cropping system, combined with reduction of pollutants in the drainage water to low concentrations that meet potential discharge and reuse standards. We propose to install a FILTER-type system with adequate modification to suit the specific site conditions. A preliminary inspection of the field site and assessment of the available information indicates that the following two modifications need to be applied to meet the site requirements: (a) subsurface drainage designed according to the regional groundwater hydrology of the site, which has more permeable soils and deeper piezometric levels than on sites previously used for FILTER; and (b) wastewater application under freezing conditions in winter.

Shanxi authorities selected a field site close to Da Tong City to install and monitor a FILTER system. Currently at this site, wastewater from a small city of around 30,000 inhabitants is subject to primary treatment. About half of the sewage effluent from the city, consisting of a flow rate around 2 ML/day, is currently discharged into a tributary of the Yang River. A part of this wastewater is used during summer as supplementary irrigation in an agricultural field close by. Three trial plots were established and instrumented in May 2004 (Figure 6). The field instrumentation is designed to allow the automated measurement of soil water content, soil pressure potential and soil temperature at various depths. A weather station was also installed at the site. The soil physical and weather data are stored in the data

Figure 6. FILTER trial site in Da Tong, Shanxi Province showing terminating boxes, cages over tensiometers and soil suction samplers in the plot in the foreground. The three terminating boxes can be seen on the three plots. The cabling between these terminating boxes and through to the data logger is buried.

logger and can be accessed through a modem. The data logger was housed in a building for security reasons and cables were run from the terminating buses in each plot, back to the house in a serial manner. The boxes holding the terminating buses are shown in Figure 6. During the spring/summer maize cropping months, excess effluent irrigation was applied to the plots. During winter months the plots were subjected to wastewater filtration through the soil without a crop.

The hydrogeology of this system was investigated to understand how a FILTER system for effluent irrigation and pollutant removal can be operated without causing unwanted environmental damage. If shallow groundwater conditions develop under the FILTER plots, it will be possible to use shallow horizontal drains to recycle water. However, if this is not the case, then deeper drainage techniques such as single or multiple strainer shallow tubewells will be needed. We also need to know the impact of increased hydraulic and nutrient loading on the regional groundwater in terms of altered groundwater regime, interaction with surface channels or pollutant contamination. Thus, we need to know where this water will move to, and its quality in the long term.

The analysis of the preliminary data on the soil physical properties at the field site and on-field observations indicates that the soils at the site have high hydraulic permeability and deep watertables. The site therefore appears to be more suitable for a modified FILTER system with a vertical drainage system, than the conventional horizontal system. On the basis of hydrogeological properties at the experimental site, a radial flow model of a FILTER site is being developed to test recharge, pumping and drawdown scenarios.

Combining FILTER with poly-greenhouses for wastewater renovation in cold winters in northern China

The harsh cold climates in northern China are an important climatic deterrent to year-round adoption of land application of wastewater for irrigated cropping such as in the FILTER system. The soils are frozen for long periods of each year. Innovative methods are needed to overcome this problem. IWHR researchers have developed a novel approach to modifying FILTER systems for application in the cold winter areas in northern China, by combining FILTER with existing poly-greenhouses (Figure 7).

In the outskirts of most cities in northern China, use of protected canopies or greenhouses is a common practice for production of vegetables and other crops to meet year-round heavy demand from urban dwellers, but these enterprises often face shortages of irrigation water. Modifying these greenhouses to combine them with FILTER technology could provide complementary benefits of potentially increased crop production and provision of low-cost wastewater renovation. Thus, in addition to using partly treated wastewater to grow specific crops within accepted health guidelines, the land FILTER systems installed under appropriately heated greenhouses can be potentially used through the cold winter months to remove the pollutants in the wastewater as it drains through the soil to the subsurface drainage systems installed beneath the poly-greenhouses. This drainage water can be discharged to natural waterbodies or be reused to help overcome the acute water shortage problems in cities in northern China.

A preliminary trial site has been established in the Beijing Water Commission area to develop and test the efficacy and potential application of the combined FILTER and poly-house technologies (Figure 7).

Potential application of FILTER technique in addressing the wastewater pollution problems in China

Wastewater pollution surveys in China indicate severe pollution in many rivers, lakes, bays, groundwater and coastal areas, due to lack of strict EPA controls in the past. The economic and environmental benefits of improved wastewater reuse in China in increasing agricultural production and preventing pollution of downstream water supplies and fisheries are well documented. In China, irrigated lands produce two-thirds of the total crop production. Irrigation is therefore a key factor influencing agricultural production in China, which is being threatened by increasing demands for domestic and industrial water (MWREP 1987; Wang 1989; CNCID 1994). The daily total water and wastewater resources available for irrigation are 7.7 and 0.1 million ML, respectively. However, during low rainfall seasons, the proportion of wastewater to total water resources can exceed 20% in the drier river basins in northern China. This propor-

tion will increase in the future (Wang 1989) and hence provides an important water resource.

It has also been recognised in China that the daily discharge of untreated sewage and industrial effluent causes serious pollution to watersheds and damages biological environments (Wang 1989; Mei and Feng 1992; CNCID 1994). In 1985, the proportions of sewage and industrial effluent that were treated before discharge were less than 3% and 22%, respectively. Many lakes and rivers close to cities receive large quantities of untreated effluent, thereby losing their previous functions of drinking water supply, recreation and aquatic production. In a survey of 878 rivers in the early 1980s, 82% were polluted to some degree and in more than 5% of total river length there were no fish. Over 20 waterways were considered unusable for agricultural irrigation because of pollution (Wang 1989). Concerns have also been expressed about the risk to public health by the use of mixed industrial and sewage effluent for irrigation of edible crops, especially from accumulation of heavy metals such as cadmium, lead, mercury and chromium (CNCID 1994). This also leads to degradation of irrigated cropping lands by pollutant accumulation. Surveys indicate that more than 85% of the pollution load in China comes from 9000 point-source polluters. The major pollutants in the waterways in China are organic matter, nutrients, heavy metals and toxic organic chemicals (Wang 1989; Mei and Feng 1992). As only 3% of the sewage effluent is treated, pathogens counts could be expected to be high near discharge points. Presence of excess nutrients in wastewater discharge can cause algal blooms in downstream waterbodies, making the water unsuitable for consumption by humans and farm animals and for other uses, as exemplified in recent outbreaks of algal blooms in Lake Dianchi in Yunnan Province.

With increasing public awareness of the importance of environmental pollution control, Chinese authorities have started introducing laws to force wastewater producers to clean their wastewater. While wastewater treatment plants may be economical in the larger, affluent cities with only limited available lands, wastewater renovation and reuse by land application systems could be more suited for smaller and less affluent cities, and for industries located in rural areas.

The specific choice of the wastewater land application system or combination-systems for providing adequate wastewater renovation without pollution risk of public water supplies will be determined by the hydrological conditions at the site, as discussed in detail by Foster et al. (2003). Figure 8, taken from Foster et al. (2003), illustrates hydrological conditions in which poorly designed effluent irrigation can lead to pollution of public water supplies, while combination systems which could involve pre-treatment with recharge lagoons or FILTER systems eliminate such risks. Thus, FILTER systems in combination with other wastewater treatment and reuse schemes could be used to overcome the water pollution concerns, in both new city planning and in solving problems of existing smaller cities and rurally located industries in China.

Figure 7. (left) Poly-greenhouses with FILTER plots, underlain with a subsurface drainage system; (right) Cheng Xianjun inspecting the drainage sump into which subsurface FILTER drainage water flows. This drainage water (with pollutants reduced below EPA limits) could be reused, or discharged into surface water bodies.
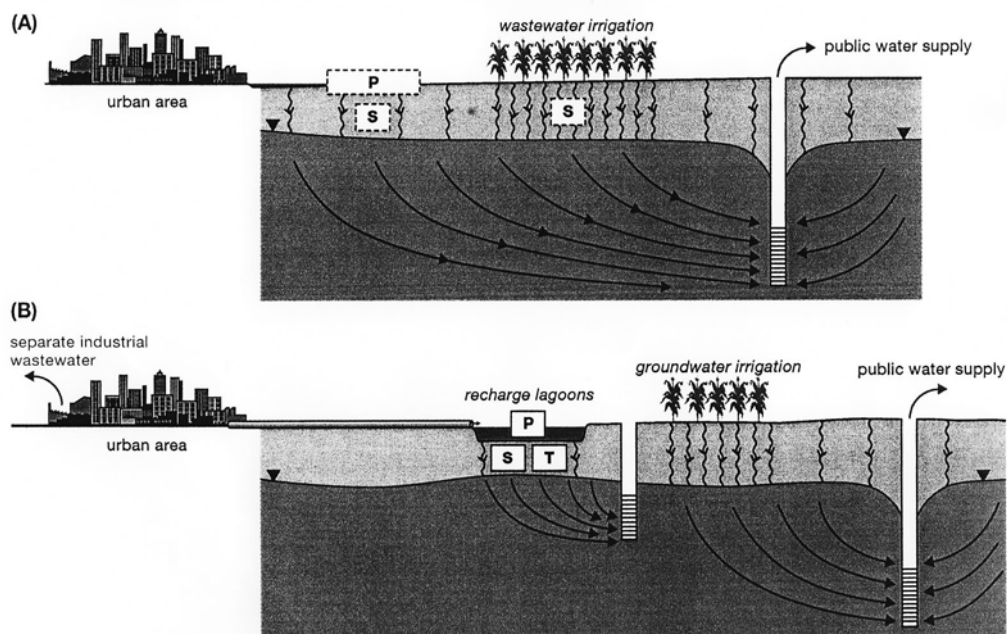
Figure 8. General schematic diagram of wastewater generation, treatment, reuse and infiltration to aquifers (from Foster et al. 2003). P, S and T denote primary, secondary and tertiary sewage treatments.
(a) Poorly designed wastewater irrigation can lead to pollution of public water supplies.
(b) Well-designed systems to reduce pollution risks, such as pre-treatment using recharge lagoons within the whole-catchment hydrological cycle. FILTER systems could substitute for the recharge lagoons, to provide an economic return through cropping. The separated industrial wastewater could also be renovated by application to small FILTER plots growing non-consumable crops, and the drainage water reused.

The optimum combination of FILTER with other wastewater treatment practices will vary widely according to specific site conditions (Jayawardane et al. 2002c). In such integrated planning, both the concerns of the environmental authorities on reducing pollution of the waterbodies and interest of the wastewater managers to reuse the wastewater economically, need to be considered. In addition, a holistic and integrated approach for combining water-supply management and wastewater reuse should be adopted, where the adequately treated wastewater can offset the demands on fresh water supplies. According to specific site conditions and available land resources, the following advantages of FILTER systems should be considered in the integrated water and wastewater management plans. The FILTER system can be sustainably used on saline, sodic, waterlogged and other degraded low-cost lands, and for dealing with saline wastewaters. A high hydraulic loading could be used

to reduce the required area of semi-urban land for wastewater renovation and the 'cleaned' drainage waters can be reused for agricultural, industrial and other uses, thereby reducing the demand on water supply requirements. As illustrated in Figure 8, the low volumes of industrial wastewater containing heavy metals should be isolated from the high volumes of domestic sewage, for separate treatment.

The producers of such wastewaters with heavy metals could be encouraged to use relatively small areas of FILTER plots to grow non-edible crops, and the cleaned wastewater draining out of these FILTER plots can be reused (Figure 8). Other innovative, optimised combinations of treatment systems incorporating FILTER could be developed according to specific local hydrological conditions. The Shanxi studies aim to provide guidelines for designing such combined systems including FILTER, to suit the local hydrological conditions.

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The perspective of farmers on why the adoption rate of water-saving irrigation techniques is low in China

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Abstract

The adoption rate of water-saving irrigation techniques in the North China Plain (NCP) has been estimated to be only 10–35%, which is low compared with 55% for better fertiliser practices. A farmer survey was conducted in 2004 to study farmers' perspectives of reasons for low adoption rates in Fengqiu County, Henan Province, NCP, where a large research project was conducted supported by the Australian Centre for International Agricultural Research (ACIAR). A multi-stage random sampling method and a face-to-face interview questionnaire were used. The total sample survey size was 210 farmers. The survey results showed that four factors contributed to the low adoption rate: perception of no need for water-saving irrigation techniques; strong risk aversion and low affordability of the water-saving techniques; lack of economic incentives; and little encouragement from extension services. A combination of both economic measures (realistic water pricing) and education (training) is suggested as a viable policy instrument to improve the adoption rate of water-saving irrigation strategies. A recommendation for future ACIAR projects is to research the dissemination of technology, as well as developing the technology itself.

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为什么先进的灌水技术在中国的采纳率很低？

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摘要： 据评估节水灌溉技术在中国的采纳率仅有 10%-35%。为了从农户的角度探讨节水灌溉技术采纳率低的原因，以河南省封丘县为研究区，于 2004 年开展了农户调查。 选择河南省封丘县是因为它是一个新近完成的以优化水肥管理为目的的大型研究项目的主研究区。该项目由澳大利亚国际农业合作研究中心资助（ACIAR LWR1/96/164）。 调查中采用了分阶段随机抽样技术以及入户式问卷调查方法。样本总量为 210。调查结果显示四个因素导致了节水灌溉技术低的采纳率。他们是农户没有使用节水灌溉技术的强烈愿望，农户高的风险回避特征和低的经济负担能力，缺乏经济激励以及弱的农业推广机制。 经济激励手段（如合理提高水价）与适当的农业推广措施相结合被认为是现阶段提高节水灌溉技术采纳率的可行措施。建议今后的 ACIAR 项目在研究技术的同时，研究适于该技术的传播机制。

关键词： 采纳率; 节水灌溉技术; 水价; 农业推广; 农户的水环境意识

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Water scarcity and water pollution are serious problems in China. Water availability in North China averages 500 m^3 per person, a figure close to the extreme scarcity level defined by the United Nations (Lasserre 2003). Groundwater has been over-exploited for several decades with the average depletion rate being 1–1.5 m per year over an area of 150,000 km^2 (Liu 2003). Over 70% of the total length of seven river systems in China has been polluted (Zhao 2004). Meanwhile, waste of water is very common in China. China has 49 million hectares of irrigated land, which accounts for 63% of total water use. However, the irrigation water utilisation coefficient (water used for crop/total water conveyed) is only 0.4–0.5, compared with 0.7–0.8 in developed countries (Liao 2004).

Many water-saving irrigation techniques have been developed in China, some of them in cooperation with countries like Australia through programs such as ACIAR-funded projects. The adoption rate of these techniques, however, is only about 10–35% (Harris 2004; Yang et al. 2004).

Adoption of agricultural technology depends on both the extension personnel and the farmers. In China, the literature on causes for the low adoption rate of agricultural technologies has focused mostly on extension agencies. However, farmers' characteristics strongly affect the rate of adoption of technology (He 2000; Wang and Lin 2002; Fu 2003, Vanclay 2004).

This paper examines the causes of the low adoption rate of water-saving irrigation techniques in China from the perspectives of farmers, so as to provide recommendations for the design of future projects.

Hypothesis and methods

Many characteristics of farmers, and of the environment they live in, affect their decision whether or not to adopt water-saving irrigation techniques. We can consider four key factors affecting adoption of irrigation techniques (Figure 1).

People's perceptions contain goals that include those achieved and those yet to be achieved. Perception can therefore be regarded as a guiding concept of behaviour and decision-making (Rahman 2003). Farmers' risk aversion and concerns about farm profitability are key factors, as water-saving irrigation techniques involve changes to farmers' traditional practices. This entails perceived risks at the early

stages of adoption and usually requires inputs of labour or money. The cost that farmers have to pay for water is another key factor, because farmers may overuse irrigation when they are required to pay only a partial cost and there are no incentives for them to adopt water-saving irrigation techniques (Harker 1998). Finally, it is commonly argued that the extension service is an important exogenous factor in promoting adoption of technology.
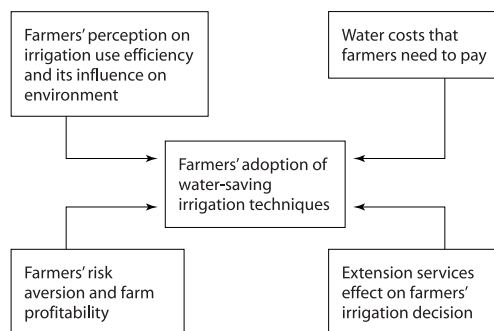

Figure 1. Factors affecting farmers' adoption of water-saving irrigation techniques

A sample group of farmers in Fengqiu County, Henan Province (Figure 2) was surveyed to examine the effect of the four factors on farmers' adoption of water-saving irrigation techniques. Fengqiu County was chosen because it was an ACIAR project site for a study on water and nitrogen management for agricultural profitability and environmental quality on the NCP (Chen et al. 2002, 2006), and water-saving irrigation practices were recommended by the project.

A multi-stage random sampling method was employed to locate towns, villages and the sample households. Sampling was conducted in consultation with local technicians and economists. The total sample size was 210 farmers and the sampled areas are encircled in Figure 2.

A questionnaire presented during a face-to-face interview was considered to be the most suitable means of gathering the required information. A sample of 10 households in Pandian Town was used to pre-test the questionnaire. The survey period was 25 May–24 July 2004.

In addition to basic socioeconomic characteristics of farmers, the questionnaire included four sections corresponding to the abovementioned four factors. The first section examined farmer perceptions about

irrigation water-use efficiency and its influence on environmental quality. Five indicators were defined to reflect irrigation and its adverse influence on the environment, based on international experience (OECD 1997, 1998). They were: irrigation water-use efficiency, fertiliser use efficiency, nitrate leaching, groundwater depletion and proportion of total water used for agriculture. Respondents were then asked to reply to each indicator based on a four-grade scale (very important, moderately important, not important, and do not care). In addition to these four grades, a fifth response category was introduced because it was found during pre-testing that respondents might have no knowledge of the concepts in the survey question. The rating scale was A (3 score) = very important, B (2 score) = moderately important, C (1 score) = not important, D (0 score) = do not care, and E (0 score) = did not know before.

The second section recorded input and output information about farms and farmers. This was to investigate farm profitability and the price paid by farmers for water. The third section was designed to evaluate levels of farmers' risk aversion and the effect of extension services on farmers' irrigation decisions. Respondents were asked: 1. which factors do you consider when you decide on your cropping pattern? 2. which factors, excluding climatic influences, do you consider when you decide on your irrigation scheduling? 3. what would you do if the water price was increased gradually? It should be noted that

each question was answered by selection from a set of multiple-choice answers. The last section included two questions: 1. what is the highest water price you could accept, if it has to be increased? 2. what are the main difficulties which have confronted farmers in production? These two questions attempted to provide additional information for policy recommendations.

Results

The survey was generally welcomed by farmers with responses from 99% of all farmers selected.

Farmers' perceptions on irrigation water-use efficiency and its influence on the environment

Although all the surveyed farmers practised irrigation and fertiliser application, 76% and 66%, respectively, did not know what was meant by irrigation water-use efficiency and fertiliser use efficiency (Figure 3). Only 12% rated nitrate leaching as 'moderately to very important'. Approximately 80% of farmers responded that they did not care about the agricultural share of total water use. Farmers said that agricultural water use is an inescapable fact of life, otherwise who would supply food to urban residents? Groundwater resources are closely related to the farmers' production, and 45% gave the response
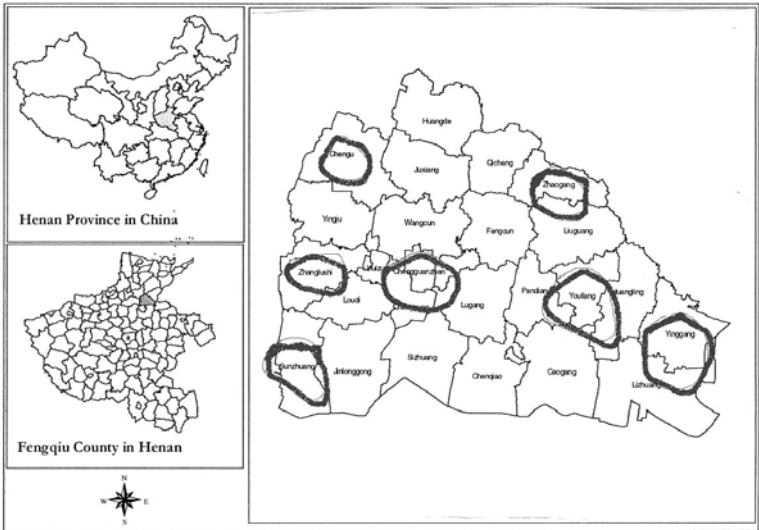

Figure 2. Town-based map of Fengqiu County, Henan Province

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'moderately to very important' to the depletion of groundwater question. This result shows that farmers lack familiarity with the concept of irrigation water-use efficiency and the adverse influence of irrigation on the environment. It therefore appears that farmers give little consideration to environmental and resource issues when they make decisions related to irrigation. Further, they did not perceive a need to adopt water-saving irrigation techniques.
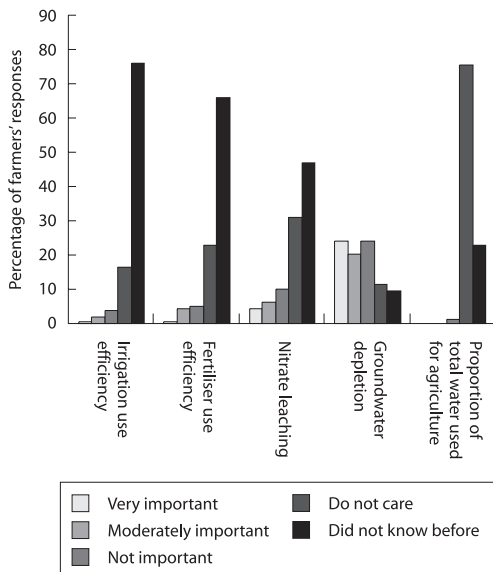

Figure 3. Farmers' perceptions of irrigation and its adverse influence on the environment

Farmers' risk aversion and farm profitability

Some 70% of respondents considered 'profit maximisation based on grain self-sufficiency' when they decided on their cropping pattern (Figure 4). Traditional habit was found to be the second-most important factor (with 45% respondents). Such high response rates on food self-sufficiency and traditional habits suggest that farmers have a strong risk-aversion, which leads to low acceptance of innovative techniques.

The annual farm income per person was 2081 Yuan (A$1 = 6.2 Yuan) (Table 1). After agricultural taxes were deducted, the disposable income was only 2026 Yuan. Although food self-sufficiency was the most common important factor, the income from grain production provides only about

one third of farmers' net income. It should be noted that labour cost is not included as an input cost of grain in China. Under such low farm profits, it is unlikely that farmers will adopt water-saving irrigation techniques that need investment or additional labour input.
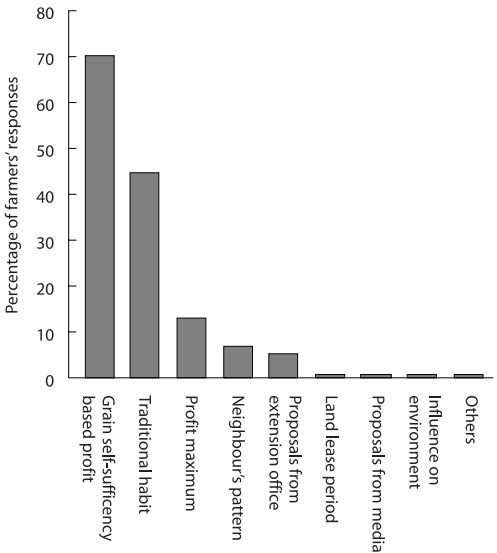

Figure 4. Factors farmers consider when they decide on their cropping pattern

Water costs farmers need to pay

In the Yellow River diversion irrigation areas, water is charged at a flat rate on the basis of land area (31.8 Yuan/mu; 15 mu = 1 ha). The price of water is about half of the water supply cost (Zhao 2004). In groundwater irrigation areas, the price of irrigation is primarily that of power for pumping and equipment — the water itself is free. Further, irrigation cost represents about 11% of total input cost and 17% of total material input cost (Table 2). This indicates that farmers lack incentives to conserve water through adopting water-saving irrigation techniques.

The effect of extension services on farmers' irrigation decisions

In China, the public extension agencies are the main transferors of agricultural technology. When respondents were asked 'Which factors do you consider when you decide on your cropping pattern?', 'Which factors, excluding climatic influences, do

you consider when you decide on your irrigation scheduling?', and 'What would you do if the water price was increased gradually?', only about 3–5% respondents ticked 'the proposals from extension agencies' (Figure 5). It appears that extension agencies have a very limited impact on farmers' decisions about irrigation. There is therefore little impetus from extension agencies to induce farmers to adopt water-saving irrigation techniques.
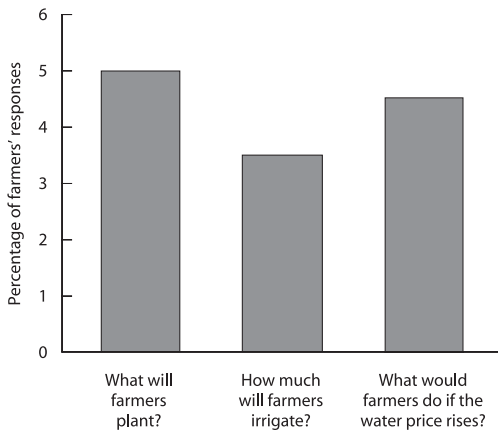

Figure 5. Effect of extension agencies on farmers' decisions related to irrigation

Policy recommendations

Generally, the farmers' perceptions of irrigation water-use efficiency and the negative influence of irrigation on the environment were weak (Figure 3). To understand the variation in farmers' perceptions of the five indicators, and hence identify potential areas for policy intervention, correlations between perceptions of the indicators and factors on which they may depend were carried out with multivariate linear regression (Table 3). It can be seen that farmers' perceptions of irrigation water-use efficiency, fertiliser use efficiency and nitrate leaching were significantly correlated with level of education (years of schooling).

In addition, farmers have strong risk aversion, as expressed in their concern about food self-sufficiency and accordance with traditional habits (Figure 4). So, the provision of education, training and extension services in intensive crop management is a feasible policy instrument. Farmers also listed agricultural technology availability as the second-most important difficulty in their production (78% of respondents), which is similar to their concern about agricultural input prices (Figure 6).

Farmers pay a partial irrigation cost, which accounts for only 11% of total input costs (Table 2). Further, water is charged at a flat rate on the basis of land area. Thus, water pricing is a feasible policy instrument to encourage farmers to use water more efficiently. However, because of extremely low farm profitability (Table 1), water pricing should be realistic. This is apparent from farmers' responses to 'What is the highest water price you could accept, if it has to be increased? (Figure 7)'. Sixty percent of respondents indicated that they could could accept only 1.2 times the current water price.

Table 1. Distribution of farmers' average annual net income per capita

Net income per capita (yuan)						Tax (Yuan)	Disposable Income per capita (yuan)
Subtotal	Grain	Non-grain in planting	Non-planting in agriculture	Non-agriculture in total production	Off-farm employment		
2081 100%	734 34.7%	450 21.2%	33 1.6%	730 34.5%	171 8%	55	2026

Table 2. Distribution of total input costs for one winter wheat crop

Total material input cost (yuan/mu)					Machine rent for sowing and harvesting (Yuan/mu)	Total input cost (Yuan/mu)
Subtotal	Seed	Fertiliser	Pesticide	Irrigation		
139 68%	20 10%	80 40%	15 7%	24 11%	65 32%	204 100%

Note: the labour cost is not included in total input cost in this table.

Table 3. Multiple regression analysis of relationships between indicators and the factors which may influence farmers' perceptions of the indictors

| Proposed indicator	Factors on which farmers' perceptions may depend	Regression coefficient	Significance	R^2
Irrigation water-use efficiency	Education Cultivation area	0.295 0.158	0.001 0.026	0.103
Fertiliser use efficiency	Education	0.475	0.001	0.225
Nitrate leaching	Education Off-farm income	0.492 0.258	0.001 0.001	0.299
Groundwater depletion	Off-farm income	0.218	0.003	0.047
Proportion of total water used for agriculture	Cropping pattern Age	0.371 0.220	0.029 0.038	0.047
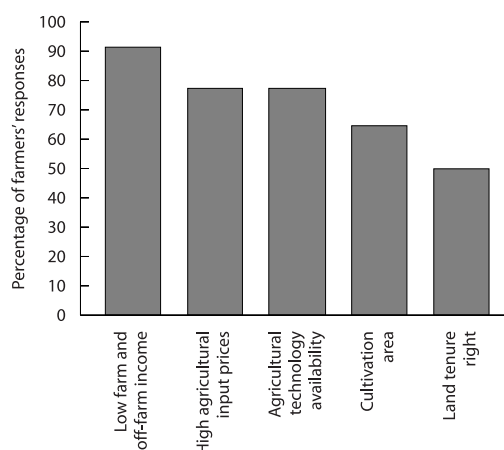
Figure 6. Main production difficulties faced by farmers in their production

Public extension agencies affected farmers' decisions on irrigation in a very limited way (Figure 5). Agricultural extension in China is regarded as being at a crossroads (He 2000; Dou et al. 2001; Wang and Lin 2002; Fu 2003; Yu 2004), requiring rapid changes. An alternative to the current situation for research projects is to have research on extension incorporated in them. The performance of the extension within the project should be progressively assessed by appropriate verification means, to find strategies for further improvement and extension to large areas after project completion.

Farm profitability and off-farm income are important factors affecting farmers' perceptions of irrigation and its negative impacts on the environment, as well as farmers' acceptability of a higher water price and their capacity to pay for new irrigation technolo-

gies. Improvement in farmers' incomes could therefore greatly promote the adoption of water-saving irrigation techniques. Farmers' income improvement is, however, a long-term social problem in China, and it needs to be considered from the viewpoint of national macro-economic policy.
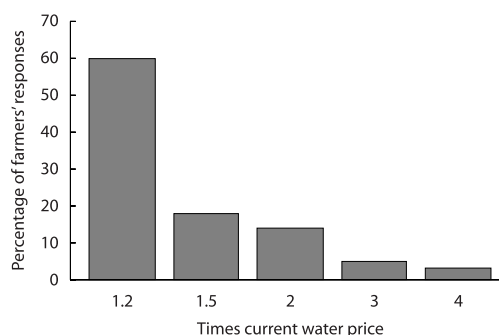

Figure 7. The highest water price farmers could accept, if it had to be increased

Conclusion

Four key reasons for low adoption rates in China were found: farmers do not perceive a need for water-saving irrigation techniques; they have strong risk-aversion and believe they cannot afford water-saving techniques; they do not have economic incentives to adopt water-saving irrigation techniques; and there is little impetus from extension agencies to induce farmers to adopt water-saving irrigation techniques.

A combination of both economic measures (realistic water pricing) and education (training) is suggested as a policy instrument to improve the adoption

rate of water-saving irrigation techniques. A recommendation for future ACIAR projects is to research the dissemination of technology in addition to the technology itself.

Acknowledgment

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