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，在高地上作物通常利用河水用地表水灌溉而在低地上的作物通常主要通过径流地下水进行灌溉。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充降低了灌溉用水效率，导致地下水埋深而引发次生盐碱化问题。如果地下水没有足够的补给水源，低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 — Luyuan Kou 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 Luyuan Kou Irrigation System in northeastern China
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 more 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](image)

**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-
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:

$$\frac{dh_1}{dt} = \left( S_{yr} + S_{c1} + P_{f1} + R_1 \right) - \left( ET_1 + GA_1 + LF \right) A_1 \cdot \text{por}_1$$

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$^2$); $\text{por}_1$ is the aquifer porosity of the upper part.

Similarly, we have:

$$\frac{dh_2}{dt} = \left( S_{c2} + P_{f2} + R_2 \right) - \left( ET_2 + GA_2 + LO \right) A_2 \cdot \text{por}_2$$

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$^2$); $\text{por}_2$ is the aquifer porosity of the upper part.

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

$$ET_i = \begin{cases} A_i \cdot ET_{0i} & h_i \geq h_{ci} \\ A_i \cdot ET_{0i} \cdot \frac{h_i - h_{ci}}{h_{ci} - h_{hi}} & h_{hi} \leq h_i \leq h_{ci} \\ 0 & h_i \leq h_{hi} \end{cases}$$

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); $h_{hi}$ 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](image-url)
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-

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**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

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

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 hydro-geological 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 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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References

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 irrigation main system operation (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。漳河灌区按照排灌的需求计划运行，在需要水的情况下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开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、确保灌区区域的可持续性。

整个过程包括了一个对灌排建筑物进行快速调查的全球定位系统，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软件进行了开发以确定供水次序。还基于Asset Manager软件开发了一套地理信息系统，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%利率情况下，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保证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服务水平的管理系统平台。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 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...
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.

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-
tation 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.

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 Irrigation main system operation (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
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.
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.

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.

<table>
<thead>
<tr>
<th>Service area</th>
<th>2003</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole system</td>
<td>0.18</td>
<td>0.23</td>
</tr>
<tr>
<td>Wenjiaxiang and Anzhankou</td>
<td>0.28</td>
<td>0.26</td>
</tr>
<tr>
<td>Heji</td>
<td>No irrigation</td>
<td>0.22</td>
</tr>
<tr>
<td>Lengshui</td>
<td>0.08</td>
<td>0.19</td>
</tr>
</tbody>
</table>

**Main canal system**

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.

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

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

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.

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.

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.
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 into 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 Objects3 and Visual Basic4 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 Wenjiazhang 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 Yuan5 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](image)

![Figure 12. Annual revenue from different users of Zhanghe Irrigation System water](image)
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/m³. 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/m³, 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.

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...
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.

References


Economic and institutional considerations for irrigation water savings

Shahbaz Khan

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“获得节约下来的水的优先权”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.

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>
<thead>
<tr>
<th>Table 1. Surface water irrigation efficiency in three irrigation systems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Key indicators</strong></td>
</tr>
<tr>
<td>Area (ha)</td>
</tr>
<tr>
<td>Losses from supply system (%)</td>
</tr>
<tr>
<td>Field losses (%)</td>
</tr>
<tr>
<td>Net surface water available to crop (%)</td>
</tr>
</tbody>
</table>

(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.

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.

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 pursuing 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.

Acknowledgments

Data inputs from the New South Wales Government departments of Land and Water Conservation, and Primary Industries, and from irrigation companies, are acknowledged. Funding support from ACIAR, the Pratt Water Group and CSIRO’s Water for a Healthy Country Flagship is appreciated.

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

A. Heaney¹, A. Hafi¹, S. Beare¹ and Jinxia Wang²

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.

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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.

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).
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 level 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).


### Table 1. Agricultural water use and farmer income, 2002

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

Data source: China Statistic Yearbook, 2003
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 efficiency 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.
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 representative 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

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

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 scarest 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.

\[
y_{ri} = \alpha_r \left( \sum_{j} \beta_{rij} x_{jri}^{\sigma-1} \right)^{\frac{1}{\gamma}}
\]

(1)

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

\( \sigma = \) elasticity of substitution

\( \beta_{rij} = \) share of input \( j \) in the production of crop \( i \) in region \( r \), with \( \sum \beta_{rij} = 1 \)

\( \alpha_r = \) 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 \( \beta_{rij} \) and \( \alpha_r \). Just as in the case of calibration of computable general equilibrium (CGE) models, for each input \( j \), the share parameter \( \beta_{rij} \) 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, \( \alpha_{ri} \), is estimated by inverting equation 1 and then substituting estimated values of \( \beta_{rij} \) and base year \( y_{ri} \) and \( x_{jri} \) values.

**Implicit land cost functions**

As the estimated share parameters, \( \beta_{rij} \) 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

\[
c_{ri} = \delta_{ri} x_{ri}^2 \quad \text{land}
\]

and thus the marginal cost by

\[
\partial c_{ri}/\partial x_{ri}=2\delta_{ri} x_{ri} \quad \text{land}
\]

The parameters \( \delta_{ri} \) are estimated by substituting the shadow prices of linear programming calibration constraints for the LHS and the base year land allocation for \( x_{ri} \) 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).

Maximize \[
\sum_{r} p_{ri} y_{ri} - \sum_{ij} \omega_{ij} x_{jri} - \sum_{ri,j} \delta_{rij} x_{jri}^2 \quad \text{land}
\]

subject to \[
y_{ri} = \alpha_r \left( \sum_{j} \beta_{rij} x_{jri}^{\sigma-1} \right)^{\frac{1}{\gamma}} \quad \text{and}
\]

\[
\sum_{i} x_{jri} \leq \psi_{j} \quad \text{resource}
\]

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

\( \omega_{ij} = \) nominal price of input \( j \) used in crop \( i \) in region \( r \) (Yuan/’000 m3 for water and Yuan/day for labour)

\( \psi_{j} = \) 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, \( \psi_{j} \).

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, \( w_{r,j} \), 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

<table>
<thead>
<tr>
<th>Region</th>
<th>Base-year water use (million m³)</th>
<th>Scarcity value of water (Yuan/ML)</th>
<th>Demand elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18</td>
<td>6</td>
<td>-0.76</td>
</tr>
<tr>
<td>2</td>
<td>1,129</td>
<td>6</td>
<td>-0.78</td>
</tr>
<tr>
<td>3A</td>
<td>3,794</td>
<td>16</td>
<td>-0.87</td>
</tr>
<tr>
<td>3B</td>
<td>1,786</td>
<td>19</td>
<td>-0.88</td>
</tr>
<tr>
<td>4</td>
<td>735</td>
<td>16</td>
<td>-0.84</td>
</tr>
<tr>
<td>5A</td>
<td>4,347</td>
<td>50</td>
<td>-1.13</td>
</tr>
<tr>
<td>5B</td>
<td>9,241</td>
<td>189</td>
<td>-1.81</td>
</tr>
<tr>
<td>6</td>
<td>3,249</td>
<td>120</td>
<td>-0.85</td>
</tr>
<tr>
<td>7A</td>
<td>8,304</td>
<td>133</td>
<td>-0.88</td>
</tr>
<tr>
<td>7B</td>
<td>15,908</td>
<td>103</td>
<td>-0.89</td>
</tr>
</tbody>
</table>

* Estimated as the net agricultural return of an additional 1000 m³ of water use in the region less delivery charges.

Regional water market model

For each region, \( d_r \), water use, is a declining function of the user price, \( p_r \). Assuming a constant elasticity specification, the demand function can be given as \( d_r = \phi p_r^{\eta r} \), where: \( \phi \) is the scale parameter and \( \eta_r \) is the elasticity of demand. For each region, the value of scale parameter, \( \phi \), 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.

Water users in region 1 lose consumer surplus measured by the trapezoidal area \( p_1 p_r^{\alpha c} \) while they gain from sales of water measured by the rectangular area \( Q_1 ab Q_1 \). The gains from trade for region 1 are thus given by \( Q_1 ab Q_1 \) less \( p_r^{\alpha c} \). Water users in region 2 gain consumer surplus measured by the trapezoidal area \( p_2 p_r^{\alpha c} \). Total net gain from trade is given by \( p_r^{\alpha c} ab Q_2 \) less \( p_2 p_r^{\alpha c} \). If water is transferred administratively rather than traded through the market, assuming the same price and quantity combinations given in Figure 1, the area \( Q_1 ab Q_1 \) represents a fair compensation payment for region 1 water users.

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

\[
p_r \geq p_s(1-t), \quad q_{rs}[p_r - p_s(1-trs)] = 0, \quad \text{for } r = 1, \ldots, 10
\]

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 offset 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.

\[
\phi_p^e + \sum q_e \leq s_i + \sum q_e \cdot (1-t_e), \quad \text{for } e = 1, \ldots, 10
\]

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.

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 production 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.

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

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

\(^a\) 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 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>
<thead>
<tr>
<th>Table 5. Benefits of water reallocation in the Yellow River Basin (million Yuan)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water-importing regions</strong></td>
</tr>
<tr>
<td>Change in value of agricultural production</td>
</tr>
<tr>
<td>Value of the water transferred</td>
</tr>
<tr>
<td>Total benefit of reallocation^a</td>
</tr>
</tbody>
</table>

^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>
<thead>
<tr>
<th>Table 6. Impact of water reallocation on farm incomes (Yuan/farm) in different regions of the Yellow River Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Region</strong></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>1682</td>
</tr>
<tr>
<td>–59</td>
</tr>
<tr>
<td>105</td>
</tr>
</tbody>
</table>

^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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References


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 (filtration and irrigated cropping for land treatment and effluent reuse) 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.
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滤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试验在天津市武清区开展。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锡、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%。总体上来看，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附特性。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、悬浮物、E. coli和在过滤过程中吸附到土壤中的农业化学物质，因而可以此排放在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 (filtration and irrigated cropping for land treatment and effluent reuse) 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
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.

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 mg/L, while the mean value in the drainage waters was 0.31 mg/L (Figure 3). 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-

Figure 2. FILTER irrigation and drainage operations, during a filter event
pended solids, BOD$_3$ and chlorophyll $a$ were also markedly reduced in the drainage waters.

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$_3$, 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 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](image-url)

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![Figure 4. Soil salinity reductions during operation of the pilot FILTER trial](image-url)

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)

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Griffith preliminary</th>
<th>Griffith pilot</th>
<th>Wuqing (5 m drains)</th>
<th>Wuqing (10 m drains)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total P</td>
<td>96</td>
<td>96</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>Total N</td>
<td>75</td>
<td>60</td>
<td>82</td>
<td>86</td>
</tr>
<tr>
<td>Suspended solids</td>
<td>81</td>
<td>68</td>
<td>81</td>
<td></td>
</tr>
<tr>
<td>BOD$_3$</td>
<td>93</td>
<td>61</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>COD</td>
<td></td>
<td>75</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td>Grease and oil</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chlorophyll $a$</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Malathion</td>
<td>99.4</td>
<td></td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Chlorpyrifos</td>
<td>100</td>
<td></td>
<td>99.8</td>
<td></td>
</tr>
<tr>
<td>Other pesticides</td>
<td>98–100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E. coli (counts)</td>
<td></td>
<td></td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

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 (IWRH), 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-
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.

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.
References


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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：经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：1）没有使用节水灌溉技术的强烈愿望，2）农户面临的风险回避特征和低的经济负担能力； 3）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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Introduction

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.

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](Image)

Figure 2. Town-based map of Fengqiu County, Henan Province


‘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.

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.

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 transmitters 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 accept only 1.2 times the current water price.

Table 1. Distribution of farmers’ average annual net income per capita

<table>
<thead>
<tr>
<th>Subtotal</th>
<th>Grain</th>
<th>Non-grain in planting</th>
<th>Non-planting in agriculture</th>
<th>Non-agriculture in total production</th>
<th>Off-farm employment</th>
<th>Tax (Yuan)</th>
<th>Disposable Income per capita (yuan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2081</td>
<td>734</td>
<td>450</td>
<td>33</td>
<td>730</td>
<td>171</td>
<td>55</td>
<td>2026</td>
</tr>
<tr>
<td>100%</td>
<td>34.7%</td>
<td>21.2%</td>
<td>1.6%</td>
<td>34.5%</td>
<td>8%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Distribution of total input costs for one winter wheat crop

<table>
<thead>
<tr>
<th>Subtotal</th>
<th>Seed</th>
<th>Fertiliser</th>
<th>Pesticide</th>
<th>Irrigation</th>
<th>Machine rent for sowing and harvesting (Yuan/mu)</th>
<th>Total input cost (Yuan/mu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>139</td>
<td>0.2</td>
<td>0.4</td>
<td>0.15</td>
<td>0.24</td>
<td>0.65</td>
<td>2.04</td>
</tr>
<tr>
<td>68%</td>
<td>10%</td>
<td>40%</td>
<td>7%</td>
<td>11%</td>
<td>32%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Note: the labour cost is not included in total input cost in this table.

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 technologies. 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.

**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.

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