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

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Abstract

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

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

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

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

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中国北方银川平原改善灌溉与排水系统的影响

摘要：银川平原坐落于黄河岸边，是中国北方最大的灌区之一，银川平原拥有庞大的灌溉排水系统。长时期的引黄灌溉引发了渍涝、次生盐碱化、地下水位高和环境污染等问题。此外，在该平原的某些地区超量抽取深层地下水引发了因浅层渗水渗漏而造成的地下水污染问题。这篇论文总结了这方面的研究成果。研究项目识别出了盐碱化和地下水位上升危险程度高的区域。浅层地下水是咸水，银川平原的人面积范围内有中度土壤盐碱化危险。大面积的地表水和地下水受到养分和盐的污染。银川平原50%以上的浅层地下水已经受到了污染。灌溉渠系向周边地区的渗漏量大，引发了地下水埋深井和土壤盐碱化问题。通过田间试验和地质化学模型判定，有50%的浅层地下水可以与地表水混合后用于灌溉，且不会使作物产量受到大的影响。如果只用地下水灌溉作物，会造成作物减产。田间试验和模型分析建议，采用喷洒代替灌溉可以节约5%的灌溉水量，且不会影响作物产量。深的明沟对降低浅层地下水位和减少盐碱化是有效的。在银川市的一些地方，应当减少从第一个承压水层中提取地下水，以避免浅层地下水的渗漏和污染。沙湖的水位应当降低0.5米，以控制其周边地区土壤盐碱化的扩散。在这些研究成果的基础上，当地政府和组织制定了盐碱化管理、地表水污染控制和灌溉排水管理的投资计划。当地政府已经在这个区域建设了3000眼井抽取浅层地下水，以便控制地下水位并补充灌溉水源。黄河向该区域的供水配额已经减少了30%。

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Introduction

Ningxia Autonomous Region is located in the northwest of China and the Yinchuan Plain occupies its northern parts (Figure 1). It covers an area of approximately 7790 km². The Yinchuan Plain is surrounded by the Helan Mountains in the west and the E’erduosi highland in the east (Figure 2). The Yellow River enters the plain from the southwestern boundary and follows along its southern boundary to the east and continues northward. The plain slopes gently towards the east and north. The plain is approximately 165 km long and varies in width between 40 and 60 km. The predominant soil types are alluvial and Podzolic (Wu and Yao 2004). There are numerous lakes and swamps in the interior parts of the plain.

Figure 1. Location of the Yinchuan Plain in China

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

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

Irrigation occurs mainly through flood and furrow irrigation. The efficiency of the irrigation system is, as a whole, very low (36%). Application rates of 15 ML/ha (1000 m³/mu) to 24 ML/ha (1600 m³/mu) are reported for crops where a crop evapotranspiration demand of 7.5–9.0 ML/ha (500–600 m³/mu) is expected. Rice irrigation is reported to be up to 49.5 ML/ha (3300 m³/mu); that is, 2–3 times the actual crop need. The cause of this poor performance is complex but includes inadequate and poor management of water distribution systems to farms and on farms, inefficient irrigation practices and low water

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

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

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

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

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

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

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

\[
\text{HRU} = \text{DTW} \times \text{RR} \times \text{HZ}
\]

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

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

<table>
<thead>
<tr>
<th>ID</th>
<th>Name of zone</th>
<th>Lithology of aquifer</th>
<th>Depth (m)</th>
<th>Aquifer yield (m³/day)</th>
<th>Total dissolved solids (g/L)</th>
<th>Depth to watertable (m)</th>
<th>Weighting factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Qintongxia pluvial fan</td>
<td>Sand and gravel</td>
<td>10–300</td>
<td>2000–5000</td>
<td>&lt;1</td>
<td>0.5–4</td>
<td>3</td>
</tr>
<tr>
<td>b</td>
<td>Pluvial gradient plain of Helan mountain foot</td>
<td>Gravel</td>
<td>&gt;100</td>
<td>1000–5000</td>
<td>&lt;1</td>
<td>5–30</td>
<td>3</td>
</tr>
<tr>
<td>c</td>
<td>Wu-Lin plain east Yellow River</td>
<td>Sand and fine sand</td>
<td>10–50</td>
<td>500–2000</td>
<td>&lt;3</td>
<td>1–5</td>
<td>6</td>
</tr>
<tr>
<td>d</td>
<td>Alluvial plain of south Yinchuan Plain</td>
<td>Mid-sand and fine sand</td>
<td>10–40</td>
<td>500–2000</td>
<td>&lt;1</td>
<td>1–10</td>
<td>5</td>
</tr>
<tr>
<td>e</td>
<td>Alluvial plain of Yinchuan</td>
<td></td>
<td>10–40</td>
<td>500–2000</td>
<td>&lt;1</td>
<td>1–5</td>
<td>5</td>
</tr>
<tr>
<td>f</td>
<td>Fluvial and lacustrine plain of Yinchuan</td>
<td></td>
<td>10–50</td>
<td>500–2000</td>
<td>1–3</td>
<td>0.5–5</td>
<td>8</td>
</tr>
<tr>
<td>g</td>
<td>Fluvial and lacustrine plain of north Yinchuan Plain</td>
<td></td>
<td>20–50</td>
<td>500–2000</td>
<td>1–5</td>
<td>0–5</td>
<td>9</td>
</tr>
<tr>
<td>h</td>
<td>Taole plain zone</td>
<td></td>
<td>100</td>
<td>500–2000</td>
<td>&lt;3</td>
<td>0.5–5</td>
<td>7</td>
</tr>
</tbody>
</table>

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

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

To assess the feasibility of conjunctive water use and use of shallow groundwater, a site was selected in the Huinong District of Shizuishan, Ningxia, where field experiments were conducted by using (1) Yellow River water; (2) Yellow River water and pumped groundwater alternately; (3) shallow groundwater; and (4) a 50:50 mixture of the two. A randomised block design was adopted and there were three replications for every treatment. Each plot had an area of 129.6 m² (3.6 × 36 m). Crops grown were spring wheat and maize planted as mixed cropping. The spring wheat was seeded on 7 March 2004 and harvested on 15 July 2004. The maize was seeded on 10 April 2004 and harvested on 1 October 2004. Five irrigations were applied during the growing season. Approximately 90 mm depth of water was applied in each irrigation. In April and October, soil samples were collected from various depths of the soil profile above the watertable for soil moisture, soil chemistry and salinity analysis. Groundwater samples were also collected to assess any changes in the quality of groundwater as a result of irrigation with varying quality water. Crop yields were measured from each plot and crop.

To assess water-use efficiency of furrow and flood irrigation methods, a site was selected in the Huinong District of Shizuishan, Ningxia, and field experiments were conducted to assess any water savings from using furrow irrigation rather than the traditional flood irrigation for growing Chinese wolfberry and evaluate impacts, if any, on crop yields and salinity build-up in the soil profile. An extensive area within the Yinchuan Plain is planted with Chinese wolfberry. The field experiments were conducted during 2003. There were two treatments (flood and furrow) with one replication for each treatment. Both treatments were planted with Chinese wolfberry. Each of the two plots in the flood irrigation treatment had an area of about 700 m² (36.6 × 19.1 m), whereas each of the two plots in the furrow irrigation had an area of 620 m² (35.5 × 17.5 m). The soil moisture from various segments of the soil profile up to 1.2 m depth was measured regularly during the growing season. Both treatments were irrigated on the same day but irrigation depths varied between two treatments.

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

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

Results and discussion

Hydrological response units (HRU) of the Yinchuan Plain

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

Water resource pollution

Total water resources available in the Yinchuan Plain are $42.33 \times 10^8 \text{ m}^3/\text{annum}$, with a surface water resource component of $25.40 \times 10^8 \text{ m}^3/\text{annum}$ and a groundwater component of $16.93 \times 10^8 \text{ m}^3/\text{annum}$ (Zhao 1999; Zhang and Wang 2003). However, the quality of the Yellow River water deteriorates on the
Yinchuan Plain due to the discharge of drainage water containing excessive salts, nutrients and other pollutants (Figure 7). Salt concentrations also increased: at the inlet of the plain (Qingtongxia) in 2002, the average concentration of total dissolved salts (TDS) of the Yellow River was 440 mg/L whereas at the outlet it was 555 mg/L.

The main drains discharged the most polluted water into the Yellow River. The pollutants included NH₄, phosphorus, chloride, sulfate, biological oxygen demand (BOD) and volatile hydroxybenzene. The TDS at the outlets of main drains was in the range 750–1740 mg/L. Water quality in the Sand Lake and West Lake also deteriorated over time. The shallow groundwater in more than 50% of the Yinchuan Plain has been polluted to some extent. Over 40% of the water samples from first confined aquifer also contained NH₄ at concentrations between 0.01 and 1.95 mg/L.

Over-exploitation of groundwater

Groundwater modelling showed that there was over-exploitation of groundwater resources in urban Yinchuan city. Over-exploitation from confined aquifers has caused excessive drawdown in the confined aquifers, resulting in downward pressure gradients and leakage of polluted water from shallow aquifers. The local government plans to increase groundwater abstraction to $2355 \times 10^8$ m³/annum during the next five years (Zhu and Xia 2002). Pumping these volumes from confined aquifers will cause excessive drawdown in the second and third confined aquifers (Table 2). To control the rate of water level decline, and therefore pollution in the second and third aquifers, the location of some of the water fields should be changed and pumping yields from the third aquifer should be reduced. The modelling scenarios and results are explained in Zhang et al. (2004a).

Soil and groundwater salinity

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

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

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

<table>
<thead>
<tr>
<th>Aquifer ID</th>
<th>2000</th>
<th>2005</th>
<th>2010</th>
</tr>
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<tbody>
<tr>
<td>II</td>
<td>14.1</td>
<td>14.1</td>
<td>24</td>
</tr>
<tr>
<td>III</td>
<td>6.2</td>
<td>6.2</td>
<td>21</td>
</tr>
<tr>
<td>III</td>
<td>350</td>
<td>1020</td>
<td>1023</td>
</tr>
<tr>
<td>II</td>
<td>248</td>
<td>700</td>
<td>992</td>
</tr>
<tr>
<td>III</td>
<td>25.4</td>
<td>25</td>
<td>33</td>
</tr>
<tr>
<td>II</td>
<td>17.2</td>
<td>14</td>
<td>40</td>
</tr>
<tr>
<td>III</td>
<td>0.31</td>
<td>1.24</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>0.39</td>
<td>2.32</td>
<td></td>
</tr>
</tbody>
</table>

Conjunctive water use

Groundwater quality data were also used in the geochemical modelling to assess the feasibility of mixing it with surface water and using it for irrigation. The plain was divided into four zones (A, B, C, D) depending upon the groundwater quality (Figure 9). The PHRREQC (Parkhurst 1995) model was used for this purpose. This model has been used for a similar study in the Ord River Irrigation Area (ORIA), northern Australia (Ali et al. 2002). The chemical composition of Yellow River water was used for canal water (CW, 498 mg/L). Representative groundwater qualities in the zones A, B, C and D were from wells W13 (2365 mg/L), W89 (1135 mg/L), W46 (955 mg/L) and W43 (1270 mg/L) respectively. The Yellow River water was mixed with the groundwater from these zones in various proportions (80:20 to 50:50) in the PHREEQC model and suitability for irrigation of the resultant water quality (salinity and sodicity risks) assessed. The modelling results showed that there will be high risk of salinity development if these mixtures are used for irrigation over long periods without providing adequate and regular leaching. Both salinity and sodicity risks will be higher in zone A of the Yinchuan Plain (Figure 9). In this zone it will be feasible to mix up to only 20% groundwater with the surface water to irrigate relatively salt-tolerant crops only. In other zones it will be safer to mix 20% groundwater with surface water for irrigation of crops. However, salt-sensitive crops will be affected by this water. Only in zones B, C and D will it be feasible to irrigate salt-tolerant crops if 50% groundwater is mixed with surface water. Heavy irrigation applications at regular intervals will be required to avoid salinity build-up in the soil profile. The use of this resource for irrigation will reduce pressures on the Yellow River water and help lower watertables on the Yinchuan Plain. Further details on geochemical modelling and results are given in Shi (2004).

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

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

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Mean yield of wheat and maize (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigation with Yellow River water</td>
<td>19.0</td>
</tr>
<tr>
<td>Mixture (50:50) of pumped water and Yellow River water</td>
<td>18.9</td>
</tr>
<tr>
<td>Irrigation with, alternately, pumped water and Yellow River water</td>
<td>17.9</td>
</tr>
<tr>
<td>Irrigation with pumped water</td>
<td>15.4</td>
</tr>
</tbody>
</table>
Irrigation techniques

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

The irrigation amounts were the same for the first two irrigations but significantly less for furrow irrigation treatment afterwards (Table 4). Total water applied in the furrow irrigation treatment was 35% less than that for flood irrigation but the average yields of wolfberries were similar for both treatments (13.3 and 13.1 t/ha, respectively). Therefore, a significant amount of water can be saved if the furrow irrigation technique is used instead of flood irrigation. The irrigation water productivities for the flood and furrow irrigation treatments were 2.2 and 3.4 kg/m^3, respectively. For the furrow irrigation method, salt would be expected to accumulate in the soil profile over time. This could be avoided by applying regular leaching applications.

Seepage from channels and drainage effectiveness

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

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

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

The monitoring of groundwater levels surrounding the Sand Lake site, and surface water levels in Sand Lake, suggested that the water levels in the lake are usually very high during the rainy season. This results in groundwater recharge, causing the groundwater levels to rise in the surrounding areas and development of additional brackish areas. Groundwater levels gradually fall away from the Sand Lake, suggesting groundwater recharge. During the dry season, the water levels in Sand Lake are generally lower, and surface water from canal and drainage system is usually pumped into the lake to maintain the water levels required. The groundwater modelling suggested lowering the currently maintained water levels in the Sand Lake by 0.5 m to reduce groundwater recharge and therefore the development of additional brackish areas. Groundwater modelling also showed that the higher, shallow groundwater heads surrounding the lake have resulted in the development of downward pressure gradients. This is causing leakage of low-quality shallow groundwater into the first confined aquifer leading to its pollution. The groundwater samples from the first confined aquifer showed higher levels of NH₄ and other pollutants, supporting the modelling results.

Conclusions

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

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

Table 4. Irrigation amounts applied in flood or furrow irrigation

<table>
<thead>
<tr>
<th>Treatment</th>
<th>15/11/02</th>
<th>19/04/03</th>
<th>11/05/03</th>
<th>11/06/03</th>
<th>28/06/03</th>
<th>11/09/03</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood irrigation</td>
<td>135</td>
<td>105</td>
<td>105</td>
<td>102</td>
<td>67</td>
<td>84</td>
<td>598</td>
</tr>
<tr>
<td>Furrow irrigation</td>
<td>135</td>
<td>105</td>
<td>33</td>
<td>42</td>
<td>39</td>
<td>29</td>
<td>383</td>
</tr>
</tbody>
</table>

50% of the area of the Yinchuan Plain has been polluted, and over 40% of the water samples from the first confined aquifer contain NH₄ above acceptable limits. In some areas of the Yinchuan Plain over-exploitation from the first and second confined aquifers is causing leakage of polluted shallow groundwater into the first confined aquifer.

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

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

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


Acknowledgment

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

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Abstract

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

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河南柳园口灌区地下水位和节水灌溉对水稻产量及水分平衡的影响研究

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摘要 应对水资源的减少，出现了不少水稻节水技术，如干湿交替灌溉（AWD）和早稻种植。然而，这些方式在不同的水文条件下的表现以及对农田水分平衡的影响还鲜有研究。本文采用模型方法，定量研究了河南柳园口灌区（LIS）地下水位和灌溉管理对水稻与早稻产量、水分生产率及水分平衡的影响。利用 4 年的大田数据对水稻模型 ORYZA2000 进行了参数化和验证，表明 ORYZA2000 可以对观察的作物与水分变量进行精确的模拟。采用 24 年的历史天气数据，在不同地下水位和水分管理组合下运行 ORYZA2000 模型，不同水分管理包括：连续浸灌（CF）；在浸水层消失 5 天和 10 天后的干湿交替（AWD）灌溉；当根区土水势降到-10，-15，-20，-30 和 -50 kPa 时进行灌溉的早稻种植，以及雨养条件种植（RF）。对于低地下水，AWD 处理和 CF 处理，由于渗透减少达 50-80%，AWD 处理可节约灌溉水 30-60%，且 AWD 处理的蒸发和蒸腾影响较小。AWD 灌溉方式可增加水分生产率（WP）达 30-60%。该地下水位的水稻产量显著地高于深水地水稻的产量。对于早稻，从灌溉指标-10 到-50 kPa，产量减少 10%，但是由于渗透的减少灌溉量减少达 80%。当灌溉指标从-10 到-50 kPa，水分生产率增加 60%。较深地下水位（20 到 120cm）的平均产量比深水地水稻（100cm）高出 39%。上述结果表明，柳园口灌区（LIS）浅层地下水位条件下干湿交替灌溉（AWD）和早稻种植可保持较高产量同时能达到节水的目的。

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Introduction

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

With the declining water availability in irrigation systems, water-saving technologies at the field scale are being developed to reduce the rice water requirement. These technologies include alternate wetting and drying (AWD), flush irrigation (FI), and aerobic rice. In AWD, the rice field is allowed to dry for a few days between irrigation events, including a mid-season drainage in which the field is allowed to dry for 7–15 days at the end of the tillering stage. The AWD system has been reported to save water and to maintain or even increase yield, and to be widely adopted by farmers (Li 2001). Belder et al. (2004) compared the effects of AWD and continuous flooding (CF) irrigations on rice performance and water use at different levels of nitrogen (N) input in typical lowland environments and concluded that biomass and yield did not differ significantly between AWD and CF, but AWD could reduce water use up to 15% without affecting yield when the shallow groundwater stayed within about 0–30 cm. A new development in water-saving technologies is the concept of ‘aerobic’ rice (Bouman et al. 2005). In the aerobic rice system, special high-yielding aerobic rice varieties are grown in unsaturated aerobic soils throughout the season, just like an upland crop such as wheat or maize, with supplementary irrigation and sufficient external inputs to reach high yields. The aerobic condition is maintained by using flush irrigation or sprinklers, so that ponding occurs for only short periods just after irrigation or rain. Aerobic rice is targeted at water-short irrigated lowlands where the availability of water is too low to grow rice under the AWD regime and at favourable uplands with access to supplementary irrigation. Research in China and the Philippines suggested that yields of aerobic rice of around 70% of that realised under CF can be obtained using about 50% of the water used in CF systems (Bouman et al. 2005; Yang et al. 2005).

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

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

### Abbreviations used

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

Materials and methods

Field experiments

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

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

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

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

Rice model ORYZA2000

Model description

ORYZA2000 simulates the growth, development, and water balance of lowland rice in situations of potential production, water limitations, and nitrogen limitations. It is assumed that, in all these production situations, the crop is well-protected against diseases, pests, and weeds. Bouman and Van Laar (2005) have presented a summary description and evaluation of ORYZA2000 for potential and N-limited situations. For water-limited conditions, the model includes soil–water balance modules PADDY (Bouman et al. 2001a,b) and SAWAH (Ten Berge et al. 1995). PADDY is suitable for typical, poorly drained lowland rice soils. SAWAH can be used for both lowland rice soils and regular ‘upland’ soils. In PADDY, a puddled lowland rice soil is modelled as a layer of muddy topsoil on top of a 3–5 cm plough sole, which overlies a nonpuddled subsoil. With ponded water on the surface, vertical water flow is either a fixed percolation rate or it can be calculated dynamically from hydraulic conductivity characteristics from the plough sole and the nonpuddled subsoil. The conductivity characteristics are expressed by either van Genuchten parameters or by parameters of a power function. With no ponded water on the surface, incoming water is redistributed by calculating gain and loss terms for all layers. All water in excess of field capacity is drained from the layer, with a maximum rate equal to the saturated hydraulic conductivity of the layer. The water reten-
tion characteristics are model input data and can be supplied either as measured data or as van Genuchten parameters. In SAWAH, the general flow equation is solved numerically under given boundary conditions, using explicit and implicit solution schemes for unsaturated and saturated layers of the soil profile, respectively. The pressure head is defined as zero at all saturated–unsaturated interfaces, and this condition is used as an internal boundary condition to calculate flow through the soil layers. For each soil layer, the conductivity curve and the water retention curve have to be specified by the van Genuchten parameters.

**Model evaluation**

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

\[
ARMSE = \left( \frac{1}{n} \sum (X_i - Y_i)^2 \right)^{0.5}
\]

\[
NRMSE = 100 \times \left( \frac{1}{n} \sum \left| Y_i - X_i \right|^2 \right)^{0.5} \sum X_i / n
\]

where \(n\) is the number of observations.

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

**Model scenarios**

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

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

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

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

\[
I + R + C = E + T + D + dW
\]

where \(R\) = rainfall, \(I\) = irrigation, \(C\) = capillary rise, \(T\) = transpiration, \(E\) = evaporation, \(D\) = deep drainage, and \(dW\) is the difference in soil water storage in the field. Total water use at the field scale is the sum of the terms on either the left or right side of the equals sign. We defined percolation (\(P\)) as \(P = I + R - E - T\); \(P\) includes \(dW\), capillary rise, and
deep drainage. If \( P \) was negative, this indicated that capillary water and water from the soil layer were used. If \( P \) was positive, this indicated that water was added to the groundwater table.

**Calculations and statistical analysis**

**Water productivity**

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

**Statistics**

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

**Results**

**Evaluation of ORYAZ2000 model**

**Model evaluation for crop variables**

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

![Figure 1](image-url)
Figure 2 compares simulated with measured grain yields for all the experiments. For reference, the 1:1 line plus and minus the SD of the measured variable is also shown. For XD90247, most of simulated yield data points fell within or very close to the 1:1 ± SD lines, indicating good simulation of yield. For HD297, the simulated yield data points fell within or near the 1:1 ± SD lines of measured ones. Generally, we see that the ORYZA2000 model provides a satisfactory simulation of grain yield for the inbred rice and aerobic rice varieties.

Table 1 gives the statistical parameters of goodness-of-fit for crop growth variables and grain yields of the whole experimental dataset. The means of simulated values were close to the measured ones. The biases (means of simulated values – means of measured values) of yield and final biomass were –121 and 1998 kg/ha for XD90247 and 199 and 405 kg/ha for HD297. The standard deviations (SDp) of simulated values were also close to the measured ones. Student’s t-test showed that the simulated and measured values of biomass of crop organs, LAI, and grain yield were all similar at the 99% confidence level. The linear relationship between simulated and measured values was highly significant, with $R^2$ values of 0.912–0.986 for XD90247 and 0.635–0.955 for HD297. The linear slope $\alpha$ was close to 1, except for LAI, with a value of 0.622, and yield, with a value of 0.751 for HD297. The intercept $\beta$ approached 0 and the $R^2$ was close to 1, except for LAI, with a value of 0.752, and yield, with a value of 0.635 for HD297.

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

Model evaluation for soil water dynamics

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

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

<table>
<thead>
<tr>
<th>Crop variable</th>
<th>NX</th>
<th>X\text{mea} (SDp)</th>
<th>X\text{sim} (SDp)</th>
<th>P(t)</th>
<th>α</th>
<th>β</th>
<th>R²</th>
<th>ARMSE</th>
<th>NRMSE (%)</th>
<th>SD</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>XD90247 dataset (2001–02)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total biomass (kg/ha)</td>
<td>39</td>
<td>4998 (4971)</td>
<td>5382 (5490)</td>
<td>0.37**</td>
<td>1.075</td>
<td>8</td>
<td>0.95</td>
<td>1350</td>
<td>27</td>
<td>622</td>
<td>12</td>
</tr>
<tr>
<td>Biomass of panicles (kg/ha)</td>
<td>21</td>
<td>2597 (2865)</td>
<td>2591 (3046)</td>
<td>0.50**</td>
<td>1.049</td>
<td>-134</td>
<td>0.97</td>
<td>502</td>
<td>19</td>
<td>257</td>
<td>8</td>
</tr>
<tr>
<td>Leaf area index</td>
<td>39</td>
<td>2.33 (1.94)</td>
<td>2.63 (2.10)</td>
<td>0.26**</td>
<td>1.032</td>
<td>0.22</td>
<td>0.91</td>
<td>0.69</td>
<td>29</td>
<td>0.43</td>
<td>17</td>
</tr>
<tr>
<td>Final biomass (kg/ha)</td>
<td>8</td>
<td>10717 (4547)</td>
<td>12715 (5355)</td>
<td>0.22**</td>
<td>1.170</td>
<td>178</td>
<td>0.99</td>
<td>2201</td>
<td>21</td>
<td>1121</td>
<td>9</td>
</tr>
<tr>
<td>Yield (kg/ha)</td>
<td>8</td>
<td>6100 (2753)</td>
<td>5979 (2831)</td>
<td>0.47**</td>
<td>0.997</td>
<td>-102</td>
<td>0.94</td>
<td>660</td>
<td>11</td>
<td>439</td>
<td>7</td>
</tr>
</tbody>
</table>

| **HD297 dataset (2003–04)**   |    |                   |                   |      |     |     |      |       |           |      |        |
| Total biomass (kg/ha)         | 96 | 2453 (2597)       | 2451 (2899)       | 0.50** | 1.091 | -225.5 | 0.955 | 653   | 27        | 365  | 14     |
| Biomass of panicles (kg/ha)   | 48 | 1251 (1272)       | 1544 (1374)       | 0.14** | 1.029 | 257.2 | 0.908 | 507   | 41        | 167  | 13     |
| Leaf area index               | 96 | 1.91 (1.95)       | 1.42 (1.40)       | 0.02** | 0.622 | 0.2   | 0.752 | 1.12  | 59        | 0.40 | 16     |
| Final biomass (kg/ha)         | 17 | 6367 (1733)       | 6772 (1813)       | 0.26** | 0.979 | 536.2 | 0.876 | 740   | 12        | 593  | 12     |
| Yield (kg/ha)                 | 17 | 2873 (869)        | 3072 (819)        | 0.25** | 0.751 | 914.0 | 0.635 | 560   | 19        | 353  | 14     |

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

<table>
<thead>
<tr>
<th>Variable</th>
<th>NX</th>
<th>X\text{mea} (SDp)</th>
<th>X\text{sim} (SDp)</th>
<th>P(t)</th>
<th>α</th>
<th>β</th>
<th>R²</th>
<th>ARMSE</th>
<th>NRMSE (%)</th>
<th>SD</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>XD90247 data set (2001–02)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth of ponded water (mm)</td>
<td>315</td>
<td>58 (37)</td>
<td>58 (37)</td>
<td>0.04**</td>
<td>0.833</td>
<td>4.07</td>
<td>0.511</td>
<td>32</td>
<td>55</td>
<td>23</td>
<td>60</td>
</tr>
<tr>
<td>Soil water tension (kPa)</td>
<td>338</td>
<td>9.236 (10.353)</td>
<td>10.335 (9.196)</td>
<td>0.48**</td>
<td>0.679</td>
<td>2.93</td>
<td>0.628</td>
<td>6.337</td>
<td>69</td>
<td>5.07</td>
<td>81</td>
</tr>
<tr>
<td><strong>HD297 data set (2003–04)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil water tension (kPa)</td>
<td>1320</td>
<td>12 (12)</td>
<td>14 (13)</td>
<td>0.00</td>
<td>0.48</td>
<td>8.159</td>
<td>0.222</td>
<td>13</td>
<td>107</td>
<td>3.81</td>
<td>52</td>
</tr>
</tbody>
</table>

N = number of data pairs; X\text{mea} = mean of observed values in whole population; X\text{sim} = mean of simulated values in whole population; SDp = standard deviation of population; P(t) = significance of paired t-test; P(t) > 0.01 means that simulated and measured values are the same at the 99% confidence level; α = slope of linear relation between simulated and observed values; β = intercept of linear relation between simulated and observed values; R² = adjusted linear correlation coefficient between simulated and observed values; NRMSE (%) = normalised root mean square error (%); ARMSE = absolute root mean square error. SD = standard deviation of measured variables; CV = coefficient of variation of measured variables.
Although the simulated values of ponded water depth exceeded the measured values in the early growing season and were below the measured values in the late growing season, the fluctuation of simulated field water depth agreed well with the dynamics of measured values.

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

Table 2 gives the statistical parameters of goodness-of-fit for ponded water depth and soil water tension of the whole dataset of XD90247 and HD297. As for crop variables, the means of the measured values were close to the simulated values. The bias (means of simulated values – means of measured values) of ponded water depth was –21 mm for XD90247; the biases of soil water tension were –1.117 kPa for XD90247 and 2.00 kPa for HD297. The standard deviations (SDp) of measured values were also close to the simulated values. Student’s t-test showed that the simulated values of ponded water depth and soil water tension and the measured values were similar at $P_c = 99\%$ for XD90247. The linear relationship between simulated and measured values was highly significant, with $R^2$ values of ponded water depth of 0.511 for XD90247 and $R^2$ values of soil water tension of 0.629 for XD90247D502 and 0.222 for HD297 at $P_c = 99\%$. The slope $\alpha$ of the regression line was close to 1 and the intercept $\beta$ was near 0 for XD90247.

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

![Figure 4](chinatek.png)

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

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

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

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

**Effects of water-saving irrigation**

**Grain yield**

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

**Water productivity**

Table 3 shows total water productivity under different WMOs. WP(I+R) ranged from 0.79 kg/m$^3$ in CF with 75 mm re-irrigation to 2.38 kg/m$^3$ in rainfed. The ANOVA results (Table 3) showed that RF had a significantly higher WP(I+R) than both AWD and CF. AWD had a significantly higher WP(I+R) than CF. AWD with re-irrigation of 50 mm 10 days after the disappearance of ponded water had a significantly higher WP(I+R) than other AWDs, whereas AWD with re-irrigation of 50 mm 5 days after the disappearance of ponded water had a significantly higher WP(I+R) than AWD with re-irrigation of 75 mm 5 days after the disappearance of ponded water. There were no significant differences in WP(I+R) between the different CF irrigations. Water productivity fell with increasing irrigation. Although the water productivity of RF is much higher, the RF yield is much lower.

**Effects of groundwater depths**

**Grain yield**

Table 4 shows the means of grain yields under different depths of the groundwater table (GWD). The mean yield ranged from 7573 kg/ha at GWD of 1000 cm to 7941 kg/ha at GWD of 20 cm. Yield decreased with increasing GWD. The ANOVA results (Table 4) showed that the yields at GWD of 20–150 cm were significantly different from the yield at GWD of 1000 cm at $P_c = 95\%$, but there were no significant differences between yields at GWD 20–150 cm and GWD 150–20 cm.
60–190 cm. Shallower groundwater depth gave higher grain yields than deeper groundwater in lowland rice production.

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

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

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

Water productivity

Table 4 shows total water productivity under different GWDs. WP(I+R) ranged from 1.13 kg/m³ at GWD 1000 cm to 1.35 kg/m³ at GWD 20 cm. WP(I+R) fell with increasing GWD. The ANOVA results (Table 4) showed that the WP(I+R)s at GWD 20–190 cm were significantly different from the WP(I+R) at GWD 1000 cm at P₉₅ = 95%, but there were no significant differences between WP(I+R)s at GWD 20–150 cm and 60–190 cm. WP(I+R) at shallower groundwater depths was higher than that at deeper groundwater depths in lowland rice production.

Water balance components

Figure 6 shows water balance components (and standard errors) under different GWDs. The rainfall value was constant. Irrigation input ranged from 349 mm at groundwater depth of 20 cm to 375 mm at 1000 cm. Irrigation at GWD 20 cm was significantly different from that at 60–1000 cm, but there were no significant differences between among 60 to 1000 cm GWDs at P₉₅ = 95%. Irrigation at 1000 cm GWD was significantly different from that at 20–190 cm at P₉₅ = 95%. Shallower groundwater depth saved irrigation input.

Evaporation was almost the same value, although evaporation at 20 cm GWD was significantly different from that at 60–1000 cm at P₉₅ = 95%. Transpiration at 1000 cm GWD was significantly lower than that at 20 to 190 cm. Percolation ranged from 163 mm at 20 cm GWD to 197 mm at 1000 cm GWD. Percolation at 20 cm GWD was significantly lower than that at 20–1000 cm, and percolation at 1000 cm GWD was significantly higher than that at 20–190 cm at P₉₅ = 95%. Percolation increased with increasing GWD. The total water input at 20 cm GWD was small because of less irrigation input. The total water input at 1000 cm GWD was also small.
but because of less capillary rise. The total water input at 60–190 cm GWD was the same.

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

<table>
<thead>
<tr>
<th>WMO</th>
<th>Yield (kg/ha)</th>
<th>WP(I+R) (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FI −10 kPa</td>
<td>4288 a</td>
<td>0.59 a</td>
</tr>
<tr>
<td>FI −15 kPa</td>
<td>4159 b</td>
<td>1.01 b</td>
</tr>
<tr>
<td>FI −20 kPa</td>
<td>4068 c</td>
<td>1.24 c</td>
</tr>
<tr>
<td>FI −30 kPa</td>
<td>3975 d</td>
<td>1.39 d</td>
</tr>
<tr>
<td>FI −50 kPa</td>
<td>3862 e</td>
<td>1.39 d</td>
</tr>
<tr>
<td>RF</td>
<td>3566 f</td>
<td>1.38 d</td>
</tr>
</tbody>
</table>

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

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

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

**Effects of water-saving irrigation**

**Grain yield**

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

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

**Water productivity**

Table 5 shows total water productivity under different WMOs. WP(I+R) ranged from 0.59 kg/m³ at the −10 kPa irrigation threshold level to 1.38 kg/m³ in RF. The ANOVA results (Table 5) show no significant differences in water productivity between WP(I+R)s at the −30 and −50 kPa flush irrigation threshold levels and RF. WP(I+R)s at the −10, −15, and −20 kPa flush irrigation threshold levels were significantly different at $P_c = 95\%$, and were significantly different from that at the −30 and −50 kPa flush irrigation threshold levels and RF. Flush irrigation at the threshold levels of −10 and −15 kPa had higher water productivities and yields. Although RF gave high water productivity, yield was low.

**Water balance components**

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

![Figure 6. Water balance components under different groundwater depths. Vertical and capped lines are standard errors.](image-url)
Evaporation ranged from 146 mm in rainfed to 181 mm at the –10 kPa irrigation threshold level. Transpiration ranged from 200 mm in rainfed to 238 mm at the –10 kPa irrigation threshold level. Evaporation and transpiration differences were not large. Percolation ranged from 226 mm at the –50 kPa threshold level to 1580 mm at the –10 kPa threshold level. Percolation in the RF treatment was negative, which indicated that the soil water supply (capillary rise) was used to satisfy evapotranspiration (ET). The trends of total water input under different water management options were the same as those of irrigation input.

**Effects of groundwater depths**

*Grain yield*

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

*Water productivity*

Table 6 shows total water productivity under different GWDs. WP(I+R) ranged from 0.08 kg/m$^3$ at GWD 1000 cm to 1.74 kg/m$^3$ at GWD 30 cm. The ANOVA results (Table 6) showed that WP(I+R)s at GWD 30 and 60 cm were significantly different from those at GWD of 90–1000 cm. There were significant differences among the WP(I+R)s at GWD 90–1000 cm. Water productivity at shallower GWDs was much higher than that at deeper ones. Water productivity fell with increasing GWD.

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

<table>
<thead>
<tr>
<th>GWD (cm)</th>
<th>Yield (kg/ha)</th>
<th>WP(I+R) (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>4645 a</td>
<td>1.74 a</td>
</tr>
<tr>
<td>60</td>
<td>4506 b</td>
<td>1.74 a</td>
</tr>
<tr>
<td>90</td>
<td>4250 c</td>
<td>1.42 b</td>
</tr>
<tr>
<td>120</td>
<td>4069 d</td>
<td>1.29 c</td>
</tr>
<tr>
<td>150</td>
<td>3949 e</td>
<td>1.07 d</td>
</tr>
<tr>
<td>190</td>
<td>3832 f</td>
<td>0.82 e</td>
</tr>
<tr>
<td>1000</td>
<td>2654 g</td>
<td>0.08 f</td>
</tr>
</tbody>
</table>

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

*Water balance components*

Figure 8 shows water balance components (and standard errors) under different GWDs. Percolation, transpiration, evaporation, and irrigation were significantly affected by different groundwater depths. Rainfall was not affected and kept the same value. Irrigation input ranged from 0 mm at GWD 60 cm to
2371 mm at GWD 1000 cm. There were no significant differences in irrigation between 30 and 60 cm GWD at \( P_c = 95\% \). Irrigation at 30 and 60 cm GWD was significantly different from that at 90–1000 cm. Irrigation increased with increasing GWD. Shallower groundwater saved irrigation input.

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

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

**Discussion and conclusions**

Agreement is relatively close between simulated and measured values of crop and soil variables. The majority of the statistical parameters and graphical comparisons show that the ORYZA2000 model is sufficiently accurate in simulating, over time, crop growth variables and yield, and soil water dynamics for inbred rice and aerobic rice under rainfed and irrigated production situations in the region. The model can be used to support field experiments in exploring the effects of management interventions (such as water management, fertiliser application, and plant density) and environmental conditions (weather, depth of the groundwater table) on the growth and development of inbred and aerobic rice varieties and water balance, with quantifiable errors of simulation.

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

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

![Figure 8. Water balance components under different groundwater depths](image-url)
tion threshold. There were falling trends in yield and transpiration from 30 to 1000 cm GWD for all water management options, and the differences of yield and transpiration increased from the –10 to –50 kPa irrigation threshold, and to rainfed conditions.

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

Acknowledgments

This paper reports on part of the work in ACIAR project LWR1/2000/030, ‘Growing more rice with less water: Increasing water productivity in rice-based cropping systems’. The authors are grateful for ACIAR’s financial support to implement this study. The authors thank Ms A. Boling and Mr Dule Zhao for their help with statistics.

References


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

M. Hafeez¹ and S. Khan¹,²

Abstract

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

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

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

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用遥感技术跟踪灌溉水量损失：中国果园灌区典型研究

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

Introduction

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

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

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

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

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

Description of the Liuyuankou Irrigation System

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

**Materials and methods**

**Satellite data**

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

**Figure 1.** Layout of Liuyuankou Irrigation System (LIS) in China

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

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

Specificity of porting SEBAL to MODIS sensor

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

The pre-processing parameters required for SEBAL include the normalised difference vegetation index (NDVI), emissivity, broadband surface albedo, and surface temperature for both sensors. The NDVI
was calculated from bands 1 and 2 of MODIS data, and the broadband albedo was calculated using weighing factors of all visible, near infrared and short wave infrared bands of MODIS (Liang et al. 1999). Surface emissivity of the sensor was calculated from the NDVI of the sensors. Surface temperature from MODIS sensors was calculated from thermal bands 31 and 32 using the split-window technique described in Wan (1999).

**Running SEBAL**

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

The ET is calculated in SEBAL (Tasumi et al. 2000; Hafeez 2003) from the instantaneous evaporative fraction, Λ, and the daily averaged net radiation, \( R_{\text{n}24} \). The latter has to be transformed from W/m² to mm/day by the \( T_0 \)-dependent latent heat of vaporisation equation inserted in the main equation (Equation 1):

\[
ET_{24} = \Lambda R_{\text{n}24}[(2.501 - 0.002361T_0)10^6]
\]

where \( ET_{24} \) = daily ET actual (mm/day) \\
\( R_{\text{n}24} \) = average daily net radiation (W/m²) \\
\( T_0 \) = surface temperature (°C).

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

\[
\Lambda = \lambda E/R_n - G_0 = \lambda E/\lambda E + H_0
\]

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

\[
R_n = \text{net radiation absorbed or emitted from the earth’s surface (radiative heat) (W/m}^2)\]

\[
G_0 = \text{soil heat flux (conduction) (W/m}^2)\]

\[
H_0 = \text{sensible heat flux (convection) (W/m}^2)\)

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

\[
ET_a = \sum_{i=1}^{n} (ET_o)(K_m)_i
\]

where \( ET_o \) = actual daily ET value computed by SEBAL for each pixel of image ‘i’ (mm) \\
\( K_m \) = multiplier for ET for the representative period \\
\( n \) = number of satellite images processed \\
\( ET \) = seasonal ET (mm).

**Results and discussion**

Daily meteorological data were collected from the Huibei weather stations and used to calculate \( ET_o \) through the modified Penman–Monteith equation.
(Allen et al. 1998). $E_{Ta}$ was converted into potential crop transpiration, $ET_c$, by multiplication with the crop coefficient $K_c (ET_c = K_c \times ETo)$. Based on the actual cropping calendar, the weighted crop coefficient $K_c$ for different satellite overpass dates was used in this study. The major crops in the LIS were rice, maize and cotton.

In this study, the pixel values of $ET_a$, calculated through SEBAL, in the area surrounding Huibei meteorological station were compared with the measured evaporation through class A pan ($E_{pan}$), estimated $ET_o$ and crop evapotranspiration ($ET_c$) from the Huibei meteorological station for the summer season of 2002 in LIS as shown in Figure 2.

There is a significant difference in ET values obtained from remote sensing and classical techniques based on weather station data. The former provides spatial distribution results, whereas the latter provides only point values.

$E_{pan}$ indicates the evaporation from water bodies. As validated in Figure 2, $E_{pan}$ value from Huibei meteorological station was always higher (on average 26%) than $ET_a$ values for all seven image acquisition dates during the season. For pixels assumed to be under a cropping area, the estimated $ET_a$ was on average 11% and 5% lower than the average $ETo$ and $ETc$ calculated from meteorological station data. The comparison provides an indication of the amount of confidence that can be placed on the values of $ET_a$ derived from the SEBAL model.

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

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

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

<table>
<thead>
<tr>
<th>ET</th>
<th>6 April</th>
<th>31 May</th>
<th>12 June</th>
<th>12 July</th>
<th>23 August</th>
<th>22 September</th>
<th>24 October</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative $ET_o$ (mm)</td>
<td>97.95</td>
<td>96.77</td>
<td>138.9</td>
<td>117.3</td>
<td>106.33</td>
<td>96.45</td>
<td>72.66</td>
</tr>
<tr>
<td>Average $ET_o$ (mm)</td>
<td>3.53</td>
<td>4.92</td>
<td>6.16</td>
<td>5.72</td>
<td>4.23</td>
<td>2.23</td>
<td>1.93</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>1–30 April</th>
<th>1–31 May</th>
<th>1–30 June</th>
<th>1–31 July</th>
<th>1–31 August</th>
<th>1–30 September</th>
<th>1–30 October</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_m$</td>
<td>27.75</td>
<td>19.67</td>
<td>22.55</td>
<td>20.51</td>
<td>25.14</td>
<td>43.25</td>
<td>37.65</td>
</tr>
</tbody>
</table>

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

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

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

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

Table 3. Seasonal evapotranspiration (ET$_s$) in LIS

<table>
<thead>
<tr>
<th>Area</th>
<th>Area (ha)</th>
<th>Minimum ET$_a$ (mm)</th>
<th>Maximum ET$_a$ (mm)</th>
<th>Mean ET$_s$ (mm)</th>
<th>Standard deviation (mm)</th>
<th>Volume (million m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above rail line (ARL) area</td>
<td>27,187</td>
<td>300.2</td>
<td>852.8</td>
<td>577.1</td>
<td>160.3</td>
<td>170.9</td>
</tr>
<tr>
<td>Below rail line (BRL) area</td>
<td>28,325</td>
<td>327.3</td>
<td>751.3</td>
<td>537.7</td>
<td>124.6</td>
<td>147.6</td>
</tr>
<tr>
<td>LIS</td>
<td>55,512</td>
<td>300.2</td>
<td>852.8</td>
<td>557.4</td>
<td>160.7</td>
<td>317.3</td>
</tr>
</tbody>
</table>

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

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

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

![Figure 4. Sensor histogram of seasonal actual evapotranspiration (mm)](image)

**Conclusion**

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

**Acknowledgment**

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**References**


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

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Abstract

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

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

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環境和体制对水分生产率和节水的影响
—从中国两处试验研究获得的启示

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

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1 Introduction

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

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

The paper is organised as follows. Sections 2 and 3 describe the physical and the institutional context and settings for the two research sites. Section 4 discusses the incentives to save or reallocate water, and the sixth through eighth sections the scope for water saving and gains in water productivity. Section 9 is concerned with scale issues in water-resource management. Section 10 presents strategies for improved water-resource management in ZIS and LIS. The final section, Rethinking irrigation, draws some general conclusions about irrigation that emerge from this study.

2 Comparing ZIS and LIS: the physical context

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

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

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

On the flat floodplains of the Yellow River, loamy soil with high percolation rates dominates LIS. There are two quite distinct zones within LIS — a natural recapture zone upstream of the railway line, and a regulated recapture zone5 downstream of the line (Figure 2). Land use upstream of the line is dominated by paddy cultivation, with water in excess of crop evapotranspiration (ET) either finding its way to drains or percolating to groundwater. The drains eventually flow to the regulated recapture zone downstream of the railway line. Farmers use drainage canals and groundwater as primary sources of water. As in ZIS, reuse is prevalent, except that LIS relies more on pumping from drains and groundwater, while ZIS uses gravity and surface storage to capture flows.

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

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

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

Comparing ZIS and LIS: the institutional context

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

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

ZIS tends to function as a demand system because of its built-in flexibility to store water in ponds and reservoirs close to the water users (Loeve et al. 2001). While farmers order water through their water user groups or village heads, many of the decisions about when to release water from the ZIS reservoir come from higher up in the canal operation hierarchy. Thus, there is a strong element of supply approach in which the reservoir operators make decisions based on the available storage, rainfall and an overall view of when the crop needs water. Our research tends to show, for example, that the decline in irrigation releases from ZIS over time (Figure 3) has put pressure on farmers to adopt alternate wetting and drying (AWD) irrigation (Cabangon et al. 2004; Moya et al. 2004), to expand ponds (Mushtaq 2004) and to recycle water (Loeve et al. 2004a). Furthermore, volumetric pricing at the village or farmer group level, adopted in the late 1980s, has provided a further incentive to save water at the village and farm level (Mao Zhi and Li 1999).

The contrast with LIS is sharp. LIS falls under the local administrative jurisdiction, outside of the command system of the Yellow River Conservancy Committee (YRCC), which controls all the division gates along the river. Though the LIS has a share of the river water, when and how much water can be diverted to the LIS depends on the availability of water in the river and the allocation plan drawn up by YRCC and the Provincial Water Resources Bureau.

Despite the fact that the Yellow River Basin is short of water, the institutional structure at LIS, coupled with a rather poorly developed infrastructure, provides no incentive and facilities for rice farmers north of the railway line (Figure 4) to save water. Because of the high watertable and high seepage from irrigation canals, practising AWD in rice cultivation is currently out of the question. Below the railway line, the picture is different, as farmers rely on pumping to grow crops other than rice.

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

<table>
<thead>
<tr>
<th>ZIS</th>
<th>LIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural recapture zone</td>
<td>Regulated recapture zone</td>
</tr>
<tr>
<td>Hilly</td>
<td>Flat</td>
</tr>
<tr>
<td>Clay loam, low percolation rate</td>
<td>Loam, high percolation rate</td>
</tr>
<tr>
<td>Drainage readily (re)captured for reuse – little salinity</td>
<td>Groundwater recharged by water from rain and other sources</td>
</tr>
<tr>
<td>Uses surface water storage</td>
<td>Groundwater main storage mechanism</td>
</tr>
<tr>
<td>Surface storage prominent</td>
<td>Irrigation and drainage channels used for recharge</td>
</tr>
<tr>
<td>Large, medium, small reservoirs</td>
<td>Pumping from groundwater prevalent, especially in downstream areas</td>
</tr>
<tr>
<td>Groundwater contributes directly to crops</td>
<td>Groundwater pumped, and contributes directly to crops</td>
</tr>
<tr>
<td>Mainly paddy rice in summer, winter wheat and rapeseeds in winter</td>
<td>Less paddy rice and a variety of upland crops in summer, mainly winter wheat in winter</td>
</tr>
</tbody>
</table>

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

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

4 Water savings and reallocation — why save water?

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

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

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

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

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

<table>
<thead>
<tr>
<th></th>
<th>Appropriation funds from the provincial government</th>
<th>Gross income from agricultural irrigation water supply</th>
<th>Net income from the city and industry water supply</th>
<th>Net income from power generation</th>
<th>Other mixed businesses</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average value (1998~2002)</td>
<td>293</td>
<td>315</td>
<td>246</td>
<td>193</td>
<td>23</td>
<td>1070</td>
</tr>
</tbody>
</table>

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

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

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

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

### Table 4. Incentives and pressures to save or reallocate water

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

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

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

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

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

### Table 5. On-farm water application for paddy growth season5 in the Zhanghe (ZIS) and Liuyuankou (LIS) irrigation systems

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigation application (mm)</td>
<td>417–470</td>
<td>512–590</td>
</tr>
<tr>
<td>Rainfall (mm)</td>
<td>407–310</td>
<td>462–360</td>
</tr>
<tr>
<td>Total inflow (mm)</td>
<td>824–780</td>
<td>974–950</td>
</tr>
<tr>
<td>Rice evapotranspiration (mm)</td>
<td>613</td>
<td>525</td>
</tr>
<tr>
<td>Yield (kg/ha)</td>
<td>7925–6500</td>
<td>7636</td>
</tr>
</tbody>
</table>

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

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

### 5 Basin and system level outcomes

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

At ZIS, in contrast, there is a need to make sure that various sectors are allocated sufficient water. This process of allocation and re-allocation is done at the sub-basin level by reservoir managers at ZIS. In con-
contrast to the Yellow River, along the Yangtze River there is evidently no great pressure to make sure more water flows in the river.

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

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

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

6 The role of secondary storage and rain

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

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

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

<table>
<thead>
<tr>
<th>Table 6. A summary of incentives to save water among the different stakeholders in the Zhanghe (ZIS) and Liuyuan Kou (LIS) irrigation systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmers – reduce application</td>
</tr>
<tr>
<td>reduce E or ET</td>
</tr>
<tr>
<td>Irrigation managers – reduce delivery to agriculture</td>
</tr>
<tr>
<td>Basin resource management</td>
</tr>
<tr>
<td>reduce E</td>
</tr>
</tbody>
</table>
lished data) shows that in normal years this may be possible, but in dry years, the reservoir provides a life-saving water source of water.

7 Response to reduced supplies

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

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

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

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

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

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

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Water release from the Zhanghe Reservoir (100 million m³)</th>
<th>Rainfall (mm)</th>
<th>Area irrigated by water from Zhanghe Reservoir ('000 ha)</th>
<th>Planted area with paddy in whole ZIS ('000 ha)</th>
<th>Yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>0.14</td>
<td>568</td>
<td>9.64</td>
<td>105</td>
<td>8.73</td>
</tr>
<tr>
<td>2003</td>
<td>0.38</td>
<td>590</td>
<td>47.44</td>
<td>102</td>
<td>7.52</td>
</tr>
<tr>
<td>2004</td>
<td>1.35</td>
<td>703</td>
<td>63.00</td>
<td>113</td>
<td>8.76</td>
</tr>
</tbody>
</table>

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

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

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

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

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

9 Scale and water resources management

The studies have amply demonstrated the importance of considering scale in agricultural water management. Considering actions at only the field scale and simply extrapolating up to system or basin level is highly likely to lead to misunderstanding. Many other factors come into play when considering water productivity at larger scales (Table 9).

![Figure 5](image.png)

**Figure 5.** Depleted fraction \(\frac{ET}{(inflow + rain)}\) estimated at different scales in the Zhanghe Irrigation System (Loeve et al. 2004). The depleted fraction (DF) available adjusts for canal inflow minus outflow across the study domain. Differences in DF across scale are due to farmer practices, influences of other land use, capture of internal run-off and reuse of drainage flows.

At ZIS, our research was aimed at understanding these cross-scale interactions. Figure 5 shows the depleted fraction \(\frac{ET}{(surface \text{ and } subsurface \text{ inflow } + rain)}\) at different scales. At field scale, the depleted fraction is quite high, because farmers carefully manage limited supplies including rain. But at a meso scale the depleted fraction drops at the study area, because the area contains forests which act as a catchment for downstream areas. Yet at larger scales, Table 9.

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

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

10 Strategies for water management at ZIS and LIS

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

• Keep as much water as possible in upstream storage (considering too the need for flood control, which requires low water levels in reservoirs at certain times of the year)
  – Reduce releases to agriculture
  – This promotes the development of internal secondary storage

• Use stored water to control reallocation to different uses
  – Water in the reservoir can be better targeted for city or hydropower use

• Promote gains in water productivity per unit of irrigation supply
  – Because farmers receive an increasingly smaller supply, AWD is a means to adapt. The same yield can be achieved with less water input from the reservoir.
  – Reduce seepage from conveyance structures to allow a higher proportion of canal water to reach farms.

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

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

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

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

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

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

11 Rethinking irrigation

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

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

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

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

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

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

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

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

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

Acknowledgments

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References


Evaluating system-level impacts of alternative water-saving options

Shahbaz Khan1, Jianxin Mu2, Yaqiong Hu2, Tariq Rana1 and Zhanyi Gao2

Abstract

Improving water-use efficiency is crucial to both Australia and China. In the case of China, development in the last half century has resulted in the irrigated area growing to 53 million ha, which accounts for 40% of the farmland. The total water used for irrigation in China gradually increased from approximately 100 billion m³ in 1949 to 358 billion m³ in 1980, since when it has stabilised. However, competition for water from other sectors is increasing. Industrial and municipal water use, for example, have increased rapidly and reduced the proportion used in irrigation from 92% in 1949, to 80% in 1980 and 65% in 1997. This situation demands major improvement in water use-efficiency for irrigated agriculture if current production levels are to be maintained or enhanced.

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

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

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

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节水方案选择的系统影响评估

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

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Introduction to a multi-scale hydrologic systems approach

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

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

1. the volume and regime of water extraction from the river; water rights definition; trading and regulation of use of water rights; improved distribution and control of water delivery to farms
2. the volume and regime of water extraction from groundwater — extraction must be matched by catchment and river recharge; improved delivery to farms
3. the volume and regime of subsurface drainage; improved management to reduce leaching and drainage to groundwater; reduction of salt load to groundwater through soil storage; improved interception of subsurface drainage water and reuse through bio-concentration and extraction; salt management schemes for subsurface drainage and groundwater
4. reduction of water extraction through greater on-farm water-use efficiency
5. improved management of surface water drainage; improved reuse; reduction of contaminants
6. land-use management to control water yield and the amounts of salt and pollutants carried to rivers and groundwater

Figure 1. Schematic of an irrigated catchment, showing with key points of intervention for water saving
7. adaptive irrigation management under circumstances of climatic variability and change.

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

Application of systems approach in Australia

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

Catchment scale

The Murrumbidgee River (Figure 2) has a catchment area of around 84,000 km² and a length of 1600 km from its source in the Snowy Mountains to its junction with the Murray River. The Murrumbidgee (MIA) and Coleambally (CIA) irrigation areas are major irrigation areas situated along the Murrumbidgee Catchment. The geographic boundaries of the Murrumbidgee catchment include the Great Dividing Range in the east, the Lachlan River Valley to the north and the Murray River Valley to the south.

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

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

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

![Figure 2. A system’s water balance: the Murrumbidgee River, Australia at catchment level 1991. All values are in gigalitres (1 GL = 10⁶ litres = 10⁶ m³)](Chinawater.book)
Irrigation area scale

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

Farm scale

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

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

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

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

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

Considering a range of soil, water and groundwater conditions, Khan et al. (2004b) concluded that on-farm irrigation technology conversions can provide potential water savings ranging from 0.1 to 2.2 ML/ha for different broadacre crops. For example, for citrus crops, they quote savings of 1.0–2.0 ML/ha for changing from flood to sprinkler irrigation and 2.0–3.0 ML/ha from flood to drip; for vineyards, the savings are 1.0–1.5 ML/ha for the change from flood to sprinkler and up to 4.0 ML/ha from flood to drip irrigation; for vegetables, they quote savings of 0.5–1.0 ML/ha. Modelling simulations show water-saving potential of 7% for maize, 15% for soybean, 17% for wheat, 35% for barley, 17% for sunflower and 38% for faba bean, if on-farm surface irrigation methods can be replaced with pressurised irrigation systems.

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

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

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

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

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

<table>
<thead>
<tr>
<th>Crop</th>
<th>Crop area (ha)</th>
<th>NCWR (ML)</th>
<th>Reported irrigation&lt;sup&gt;a&lt;/sup&gt; (ML/ha)</th>
<th>Reported yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>46,120</td>
<td>506,562</td>
<td>11.0</td>
<td>14.0</td>
</tr>
<tr>
<td>Wheat</td>
<td>39,215</td>
<td>111,835</td>
<td>2.9</td>
<td>2.0</td>
</tr>
<tr>
<td>Oats</td>
<td>2,896</td>
<td>7,512</td>
<td>2.6</td>
<td>2.0</td>
</tr>
<tr>
<td>Barley</td>
<td>3,034</td>
<td>8,615</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Maize</td>
<td>2,924</td>
<td>18,813</td>
<td>6.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Canola</td>
<td>2,685</td>
<td>4,643</td>
<td>1.7</td>
<td>2.5</td>
</tr>
<tr>
<td>Soybean</td>
<td>2,881</td>
<td>18,383</td>
<td>6.4</td>
<td>8.0</td>
</tr>
<tr>
<td>Summer pasture</td>
<td>3,929</td>
<td>45,154</td>
<td>11.5</td>
<td>7.5</td>
</tr>
<tr>
<td>Winter pasture</td>
<td>24,184</td>
<td>50,403</td>
<td>2.1</td>
<td>5.5</td>
</tr>
<tr>
<td>Lucerne (uncut)</td>
<td>2,468</td>
<td>43,291</td>
<td>17.5</td>
<td>10.0</td>
</tr>
<tr>
<td>Vines</td>
<td>13,635</td>
<td>77,508</td>
<td>5.7</td>
<td>5.0</td>
</tr>
<tr>
<td>Citrus</td>
<td>8,700</td>
<td>68,861</td>
<td>7.9</td>
<td>7.0</td>
</tr>
<tr>
<td>Stone fruits</td>
<td>934</td>
<td>9,071</td>
<td>9.7</td>
<td>9.0</td>
</tr>
<tr>
<td>Winter vegetables&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1,500</td>
<td>921</td>
<td>0.6</td>
<td>5.0</td>
</tr>
<tr>
<td>Summer vegetables&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1,500</td>
<td>8,906</td>
<td>5.9</td>
<td>7.0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>156,605</strong></td>
<td><strong>980,477</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Reported irrigations levels are subject to adjustment for measurement error; e.g. 14% is the accepted underestimation factor for Dethridge wheels.
<sup>b</sup> Irrigation requirement and yield is for onions. For salad crops (lettuce) irrigation requirement is 2.0–4.0 and yield is 3.0–4.0.
<sup>c</sup> Irrigation requirement and yield is for tomatoes. For melons, the irrigation requirement is 4.0–7.0 and the yield is 3.0–4.0.
<sup>d</sup> Reported gross diversions for 2000–01 are 1,048,000 ML and on-farm deliveries 857,000 ML.

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

**Application of systems approach in China**

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

The model is capable of depicting surface and groundwater balances separately and allowing depiction of interaction between them, as well as impacts of storage and depletion through withdrawals. Figure 5 is a schematic depiction of the model.

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

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

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

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

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

<table>
<thead>
<tr>
<th>Crop</th>
<th>Irrigation method</th>
<th>Water savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface</td>
<td>Sprinkler</td>
</tr>
<tr>
<td></td>
<td>High  Low Average</td>
<td>High  Low</td>
</tr>
<tr>
<td>Maize</td>
<td>10.6  4.3  8.3</td>
<td>9.2  4.0  7.7</td>
</tr>
<tr>
<td>Soybean</td>
<td>6.6   3.6  5.4</td>
<td>5.6  3.2  4.6</td>
</tr>
<tr>
<td>Wheat</td>
<td>4.2   0.5  2.4</td>
<td>2.8  0.5  2.0</td>
</tr>
<tr>
<td>Barley</td>
<td>4.3   0.7  1.7</td>
<td>2.4  0.7  1.1</td>
</tr>
<tr>
<td>Sunflower</td>
<td>7.0   3.5  4.6</td>
<td>4.8  3.1  3.8</td>
</tr>
<tr>
<td>Faba beans</td>
<td>4.9   1.5  3.2</td>
<td>3.3  1.4  2.0</td>
</tr>
</tbody>
</table>
Figure 5. Schematic of the basin-wide holistic integrated water assessment model

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

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

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

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

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