

Improving Irrigation Water Use Efficiency, Productivity and Equity. Simulation Experiments in the Downstream Yellow River Basin

Nicolas Roost

International Water Management Institute (IWMI), Colombo, Sri Lanka

Email contact: IWMI@cgiar.org

Abstract

Irrigated agriculture is put under simultaneous pressure to supply the needs of a fast growing population and to release water for other, higher valued uses. In this context, solutions have to be devised to make a substantially more efficient and productive use of water in irrigation. This paper introduces a new irrigation model, OASIS (*Options Analysis in Surface Irrigation Systems*), which was developed to conceptualize and test irrigation interventions in a medium to large-scale irrigation system. OASIS integrates recycling and captures all the main factors of the water balance, including non-process depletion from fallow lands and non-crop vegetation. Based on its innovative skills, the model allows proper quantification of water use efficiency, productivity and equity under actual or hypothetical conditions of land use, infrastructure and water management. The main outcomes of the OASIS model application in the Bojili Irrigation District (BID), a large-scale irrigation scheme located in China's lower Yellow River basin, are presented. The analysis undertaken emphasizes the critical importance of properly accounting for the capture and recycling of irrigation return flows to develop a meaningful picture of how water is being used. Ultimately, this analysis suggests that integrated modelling tools like OASIS can bring very valuable support to identify opportunities and means to improve water use efficiency, productivity and equity in water-short areas such as the Yellow River basin.

Improving Irrigation Water Use Efficiency, Productivity and Equity. Simulation Experiments in the Downstream Yellow River Basin

Nicolas Roost

International Water Management Institute (IWMI), Colombo, Sri Lanka

Email contact: IWMI@cgiar.org

1. Introduction

Irrigated agriculture has been an essential factor of food security in the last decades. In the future, it will most probably be called upon to produce a large fraction of the increased food supply needed by a rapidly growing world population. At the same time, agriculture will however have to cope with increasing competition for water. In particular, the diversions to meet the requirements of urban and industrial growth are expected to rise substantially in developing countries, thereby diminishing the share of agriculture in several major river basins where water resources are already fully or near fully utilized.

In a context where water scarcity will certainly emerge as the key constraint to agricultural production, there is a pressing need to achieve a substantially more efficient and productive use of water in irrigation. Addressing this need, however, requires a better understanding of the water balance within irrigation projects. In particular, the recycling of irrigation return flows (the non-consumptive ‘losses’ occurring as canal seepage, surface runoff and deep percolation), which often plays a key role in water-scarce areas, needs more careful consideration.

Recognizing the complexity of irrigation projects and the failure of existing irrigation models to consider all important sources and uses of water within such projects, a new, more integrated model was developed. This model, OASIS (*Options Analysis in Surface Irrigation Systems*), integrates recycling and captures all the main factors of the water balance within an irrigation project. OASIS was applied for scenario analysis in the Bojili Irrigation District (BID), a large-scale irrigation scheme located in China’s lower Yellow River basin. The present paper introduces the model and its application in China. Through the BID case study, this paper intends to demonstrate the value of an integrated modelling approach to help identify opportunities and means to improve water use efficiency, productivity and equity in water-short areas such as the Yellow River basin.

2. Overview of the OASIS simulation model

Background

To date, irrigation modelling has put a large emphasis on canal water delivery and on-farm irrigation management, addressing specific needs of irrigators and scheme managers. However, it has certainly provided very limited support to water planners and policy-makers at large. The essential reason is that irrigation models generally focus on a limited portion of the water balance, missing important sources and uses of water within irrigation projects. In particular, they fail to consider the possible capture and recycling of irrigation return flows. Yet, recycling of return flows can have a major impact on water use efficiency, productivity and equity, especially in conditions of water scarcity.

OASIS (Roost, 2002) was designed so as to address the main shortcomings of other irrigation models. It is based on an integrated modelling framework that comprises a conceptual representation of the main irrigation system components – including the groundwater and drainage systems – and their interactions (Figure 1). OASIS brings in several innovative skills, notably:

- The capacity to capture all main factors of the water balance within an irrigation project, including non-process depletion from fallow lands and non-crop vegetation;
- The ability to capture and consider recycling of irrigation return flows, thus allowing conjunctive canal, groundwater and drainage water use;
- The capacity (based on the above skills) to properly quantify water use efficiency, productivity and equity under actual or hypothetical conditions.

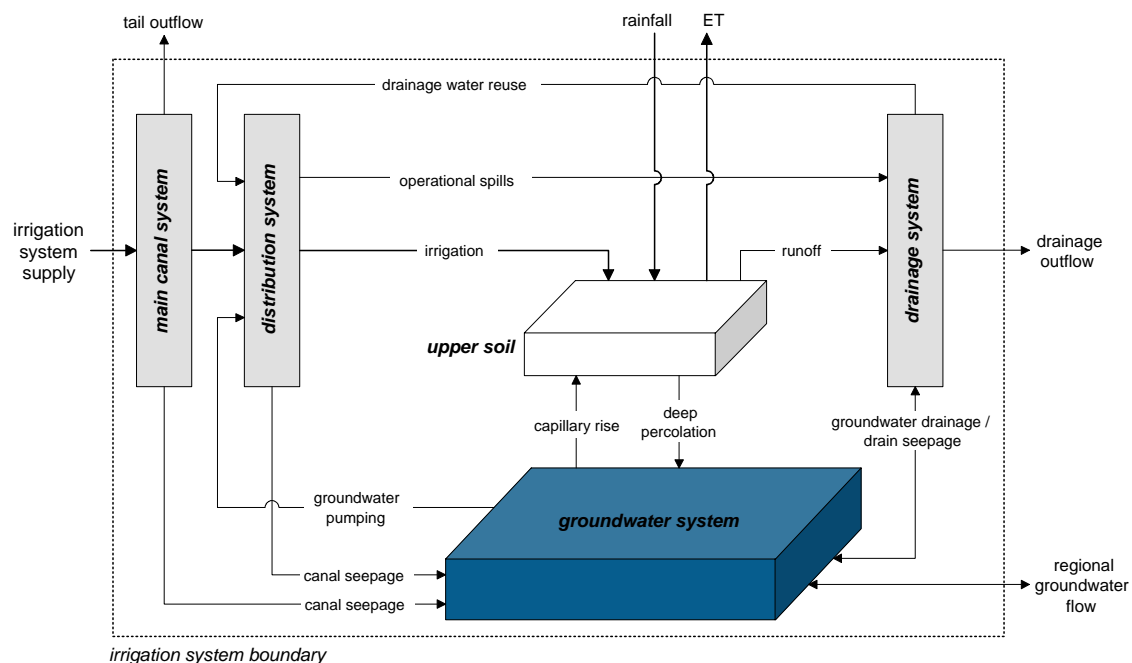


Figure 1. Synoptic view of the OASIS model components

Modelling framework

OASIS simulates the functioning of a medium to large-scale irrigation system over an irrigation season or a year, considering actual or hypothetical land use, infrastructure characteristics and water management practices, as well as given climatic and resource availability conditions (Figure 2). It then evaluates indicators of water use efficiency, productivity and equity, which allow valuing alternatives on a comparative basis and provide relevant support for strategic decision-making in a basin-wide water resources framework.

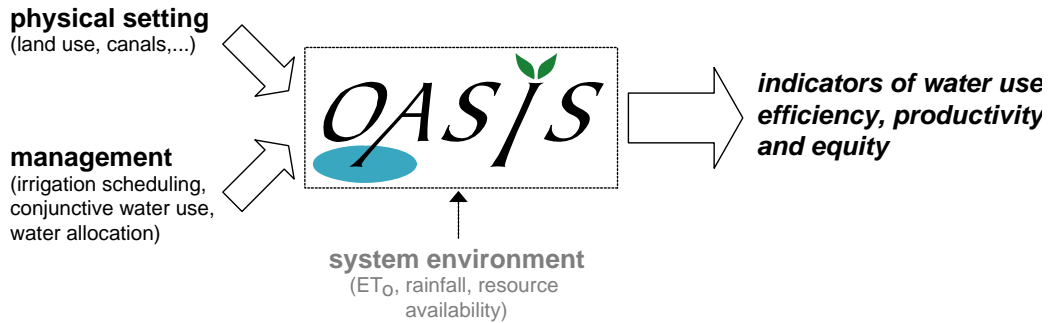


Figure 2. The basics of OASIS

The modelling framework of OASIS encompasses a hierarchical structure built on three distinct levels, namely the *field*, *sector* and *irrigation system* levels. OASIS defines an *irrigation system* as the command area of a main canal (or a main canal network) diverting water from a single source such as a river, a reservoir, a pumping station or another irrigation canal.

To account for the large-scale spatial variability of soils, land use, infrastructure, water availability and management, OASIS models an irrigation system as a set of interdependent geographical units referred to as *divisions* and *sectors*. A *division* is defined as the command area pertaining to a delimited reach of main irrigation canal. A *sector* is subsequently defined as the part of a division situated on one given side of the main canal (Figure 3). Each division thus includes two sectors if irrigation takes place on both sides of the main canal and only one sector, otherwise. Sectors are characterized in a lumped manner, assuming that nothing is known about where features are located or how they are spatially distributed within their boundaries. Each sector is assumed to possess its own (independent) distribution, groundwater and drainage systems¹. Sectors are absolutely central to the OASIS modelling framework: they define at the same time the basic descriptive and evaluation units of the model. Accordingly, sectors identify the actual spatial resolution of this model.

¹ The groundwater system of a sector is modelled as a horizontal reservoir; the drainage system is represented as two levels of channels with a horizontal surface water level. The interaction between these surface and underground 'reservoirs' is controlled by a linear flux-head relationship.

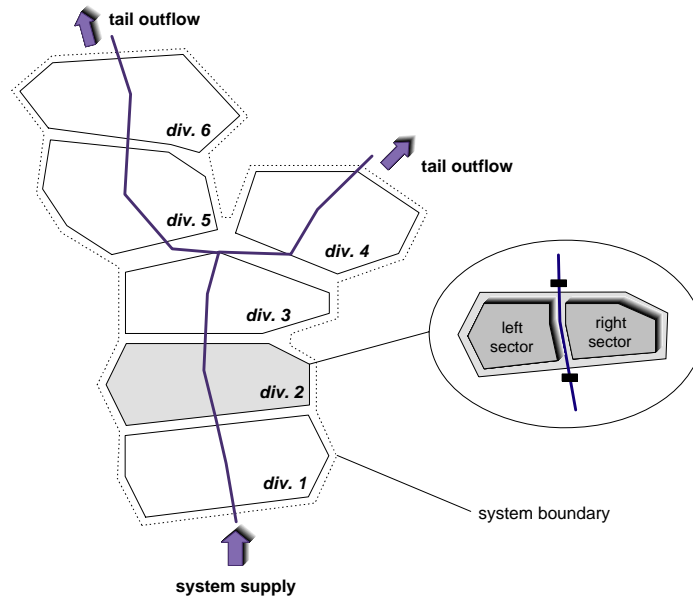


Figure 3. Illustration of the *division* and *sector* concepts

To account for the smaller-scale, intra-sector variability of soils, land use, irrigation practices and water availability, OASIS associates each sector with a set of *fields*. *Fields* are conceptual land use units, each characterized by specific soil and land cover properties. They are not located in space and are modelled as point entities. Fields are generated by the model from the lumped description of sectors so as to provide a proper representation of the soil and land use variability in these sectors. It is at the field level that the soil-crop-water interactions are simulated. The core structure of OASIS, built on the system, sector and field levels, is illustrated in Figure 4.

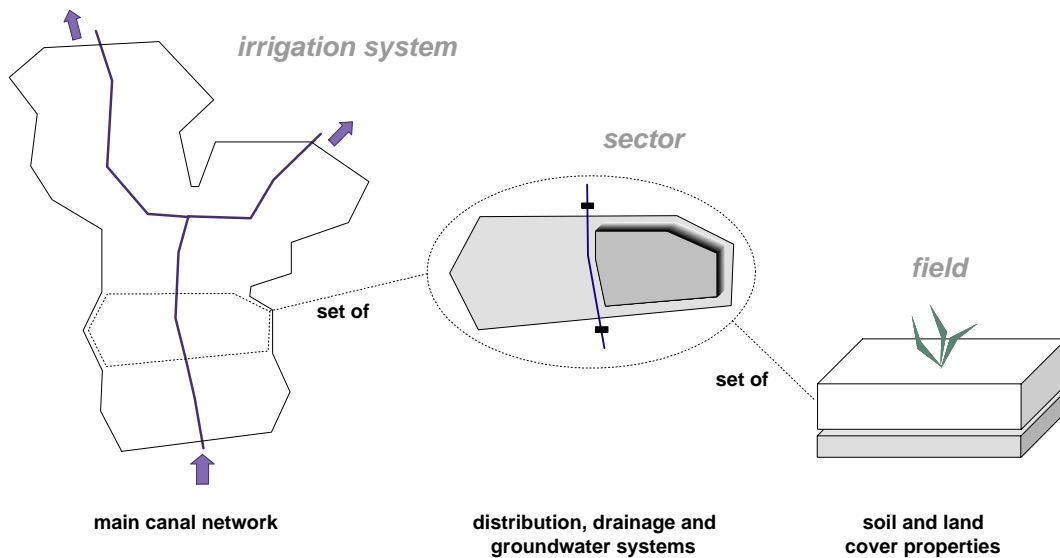


Figure 4. The three-level structure of OASIS

Simulation process

To make it possible to (at least in most cases) ignore water conveyance time lags, the basic time step of OASIS was set to 10 days. Since proper assessment of the soil moisture and crop status requires that the timing of rainfall or irrigation events be considered with more precision, a daily calculation time step is however applied for dealing with all the processes that are internal to sectors (e.g., irrigation water distribution and soil water balance).

The overall simulation process of OASIS relies on three main (sub-) processes, successively executed during each basic time step (10-day period) of a simulation:

1. Assessment of the water demand of each sector;
2. Simulation of a system-level water allocation pattern;
3. Assessment of the response of each sector to the simulated water supply.

The ultimate goal of the first two processes is to obtain, for each sector, a main canal water allocation that is representative of the prevailing conditions of irrigation requirements and resource availability during the 10-day time step under consideration. The third process then intends to evaluate the effect of the simulated supply on the different components modelled in each sector.

The water demand of a sector is calculated by aggregating the irrigation requirements of the fields this sector is associated with. The process also considers a possible contribution from local supply sources, including groundwater and surface water stored in drainage canals. Local supply sources, managed according to specific rules, thus possibly act as a buffer on sector demands for main canal supply. Depending on the selected rules of irrigation scheduling², the model performs soil water balance over the 10-day period under consideration to determine the irrigation requirement of each field.

Sector water demands constitute the main input to the system-level water allocation process. This process takes into account the physical constraints of the main canal network, the water resource availability at the head of the irrigation system, the water allocation policy, and possible downstream water requirements. An algorithm built on linear programming makes it possible to allocate water based on priorities or following an equity principle (all demands satisfied in the same proportion).

The simulated water supply, made of the water allocated from the main canal network and including a possible contribution from local water sources, is daily distributed to the fields for which irrigation is required or scheduled. Still on a daily basis, the model computes the soil water balance of each field to keep track of its soil moisture status. It subsequently performs water balance of the groundwater and drainage systems to model the state variations of these two reservoirs in each sector. At the end of the 10-day time step, the simulated daily water fluxes are aggregated and the various terms of the overall sector and system-level water balance (see Figure 1) are updated. These terms constitute

² OASIS can incorporate widely different types of irrigation schedules, ranging from the most rigid (fixed frequency and depth) to the most flexible (on-demand).

the building blocks of the indicators used by OASIS to quantify water use and overall irrigation performance in a system under study. A detailed description of the OASIS model is provided by Roost (2002).

3. General description of the study area

Bojili Irrigation District (BID) is a large-scale surface irrigation system located in the Shandong province (37.30°N, 117.50°E) – the last province crossed by the Yellow River before it discharges to the Bohai Sea. BID was created in 1966. It presently commands a nominal area of 110'000 ha, which partly covers three counties (Huimin, Yangxin and Wudi). A basic map of the district, including the primary and secondary irrigation canals, and showing the seven divisions delimited for this study is given in Figure 5. The two most downstream divisions (greyed on the map) were not included in the analysis due to lack of descriptive data.

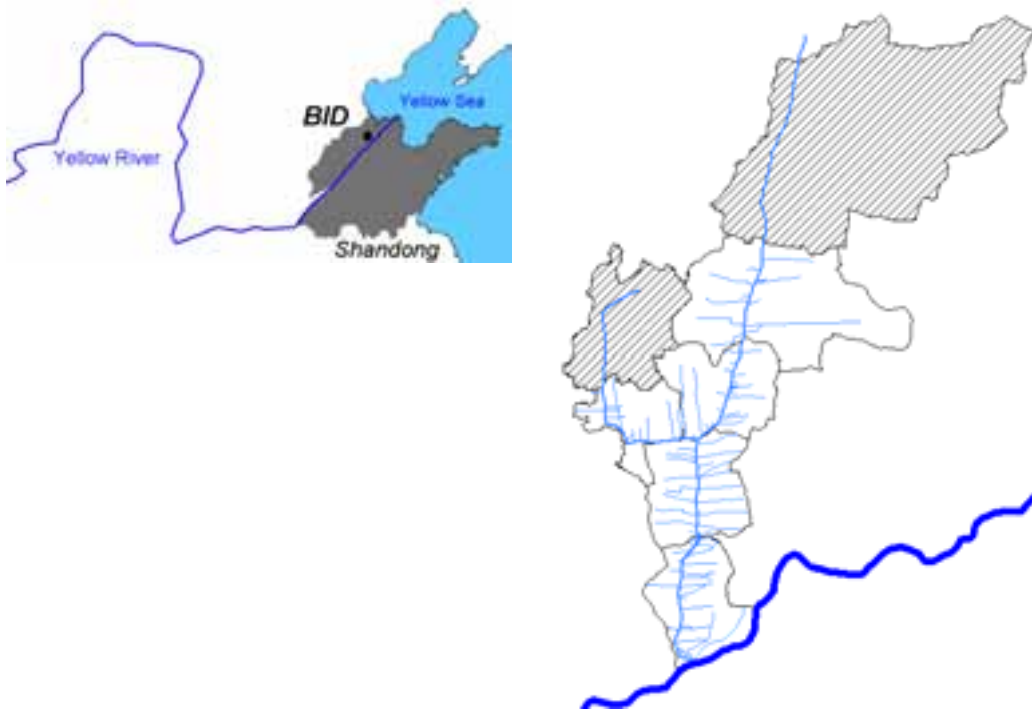


Figure 5. The BID scheme and its location in the Yellow River basin

Rainfall in BID averages 550 mm, but exhibits high interannual variability, both in terms of total annual depth and seasonal distribution pattern. Rainfall mostly occurs from June to September, a period during which irrigation is largely supplemental. The average annual reference evapotranspiration (ET_o) approximately amounts to two times the average annual rainfall depth. Soils in the district are fine-textured (mostly silt loams) with a high water holding capacity. The main crops grown include wheat during the winter season and maize during summer. Cash crops such as vegetables and fruit trees

occupy a significant proportion of the district area. The cropping intensity is approximately 150% in the district.

To cope with scarce and poorly reliable canal supplies, storage and recycling have been widely developed in BID. The storage strategy relies on three elements:

- The shallow aquifer underlying the district area, which captures abundant canal seepage and field percolation fluxes, and is exploited through thousands of wells;
- The drainage canals, equipped with gates and earth dams to conserve the collected runoff³;
- Large reservoirs for irrigation water supply (Wudi county only).

Water delivery is not planned in the district, which is essentially a consequence of the low reliability of river supplies. Decisions on when to irrigate are primarily controlled at the township level. The extensive use of local sources of water however provides a certain level of flexibility to farmers in scheduling irrigations. Basin irrigation is by far the most common irrigation method in BID.

4. Scenarios and impacts

The OASIS model application in BID could take advantage of a substantial amount of data produced by the EU-funded project '*Policies for water savings in the Yellow River basin: a DSS applied to Ningxia and Shandong*' (Pereira *et al.* 2000). This model application however had to cope with large knowledge gaps, both regarding the physical setting and water management. In particular, little is known about the drainage system characteristics, the irrigation practices (conditions in which different crops are irrigated in the district) and the conjunctive water use practices (management rules of the different sources of irrigation water exploited in the area and volumes involved). As a result, a number of large assumptions had to be made to model BID. For this reason, we highly recommend more detailed investigations before any specific action is taken.

In the absence of a sufficiently well defined current situation, a scenario, which integrates the maximum number of known or assumed facts about the current system, was designed to serve as a reference basis for evaluating potential improvements to the system performance. To define this reference scenario, it was in particular assumed that:

- Upstream divisions get priority over downstream divisions for allocation of main canal water;
- Crops are irrigated on a fixed frequency, variable depth basis⁴; a special on-demand irrigation treatment was however considered for vegetables;
- The drainage system is only kept 'open' while in the heart of the rainfall season.

These assumptions yield a fair representation of: 1) the higher reliance on local sources of water and the higher potential for shortages downstream; and 2) the high degree of

³ Sub-surface drainage seems to play only a minor role in the BID area.

⁴ Irrigation depths are calculated so as to refill the root zone to field capacity and irrigation is only applied, on each turn, if the soil moisture lies below a defined threshold value. A higher irrigation frequency was considered for upstream divisions, having an easier access to water.

hydrological closure of the district. The crop areas in 1995, as available from township-level statistics, were taken as reference. It was admitted that the whole area under cultivation can be irrigated. An additional area, taken as 10% of the cultivated area, was considered barren, which for example partly accounts for permanent fallow lands, unpaved ways, and channel embankments. Natural vegetation is not very significant in the district and was not taken into account.

The daily meteorological conditions of 1999, a dry year⁵, were used for simulations. A (river) resource availability constraint was taken into account and defined as the inflow hydrograph recorded at BID headworks in that year. The two most downstream divisions of the district (western part of Yangxin and southern part of Wudi) were indirectly taken into consideration by reproducing the main canal inflows recorded at the head of these divisions. Focus was set on a period extending from January to September, thereby including the spring irrigation and the rainfall seasons.

According to the classical conception of efficiency, which ignores the value of irrigation return flows (Keller and Keller, 1995), BID would be regarded as a poorly efficient system. There is indeed a large fraction of the water input that is ‘lost’ as seepage in the conveyance and distribution canals or as deep percolation when water is applied on-farm. Since rehabilitation programs often put a strong emphasis on the reduction of such ‘losses’, example is taken here of an improvement scenario assuming that a series of measures (e.g., canal lining and precision land leveling) is taken to halve distribution and on-farm inefficiencies. Table 1 shows that such measures would result in a significant reduction of the amounts of diversion (-12%) and pumping (-15%), which would lead to lower irrigation costs. The impacts on water productivity would however be minor, since the yields and the overall level of water availability are similar in the two cases.

Table 1. Selected simulation outputs for the ‘reference’ and ‘improved efficiencies’ scenarios. Note: equivalent depths are calculated relative to the total (estimated) cultivated and permanent fallow area in the five modelled divisions

		Reference	Improved efficiencies
<i>river diversion</i> ^(a)	[mm]	392	346
<i>depletion</i>	[mm]	681	688
<i>pumping</i> ^(b)	[mm]	189	160
<i>productivity of available water</i> ^(c)	[Yuan m ⁻³]	4.93	5.01
<i>economic loss of production</i> ^(d)	%	2.8	1.8
<i>storage change</i>	[mm]	76	36

(a) The water committed to the two most downstream divisions (divisions 6 and 7, not modelled) was subtracted. (b) Includes groundwater pumping and drainage water reuse. (c) Water accounting indicator forwarded by Molden (1997). (d) Defined as the gap between the maximum gross value of production, achieved when no water stress occurs, and the actual gross value of production.

⁵ Based on a statistical analysis over the period 1971-1999, the empirical exceedance probability of the 474 mm rainfall recorded in 1999 is 75%.

The significant reduction of the system diversion gives a strong feeling that water is saved. It is however worthwhile noting that the final storage in the system is approximately reduced in the same proportion as the diversion. Since water depletion remains almost constant, water savings are only apparent (or fictitious) and the most important difference among the two scenarios appears to be that they allow to store more or less water in the system. This storage – actually almost exclusively groundwater storage – constitutes a reliable source of water that can support irrigation during subsequent low flow periods. For both scenarios, the estimated fraction of available water⁶ depleted within the district area exceeds 90%, with crop ET accounting for about the same fraction of the total depletion. These figures highlight the high overall efficiency of the study area, intimately related to the extensive capture and recycling of irrigation return flows.

To extend the analysis, an additional scenario was considered, which is based on a physical setting similar to the reference scenario, but assumes equitable allocation of water among sectors. This new improvement scenario stands apart from the previous in that it is non-structural and does not directly target higher efficiencies. A higher level of water stress was considered, with the (river) resource availability set at 65% of the diversion recorded in 1999⁷. Table 2 compares some simulation outputs for the reference and the two improvement scenarios under these new resource availability conditions.

Table 2. Main outputs for the selected scenarios under reduced resource availability conditions

		Reference	Improved efficiencies	Equitable allocation
<i>river diversion</i>	[mm]	300	277	302
<i>depletion</i>	[mm]	664	678	669
<i>pumping</i>	[mm]	261	218	282
<i>productivity of available water</i>	[Yuan m ⁻³]	4.99	5.07	5.08
<i>economic loss of production</i>	%	4.7	2.8	3.5
<i>storage change</i>	[mm]	8	-19	14
<i>watertable level change</i>	[m]	0	-0.26	0.15

The figures presented in Table 2 indicate that the reduction of the resource availability results in a very substantial increase of pumping but does not really affect depletion.

⁶ Following Molden (1997), the available water is defined as the total inflow from diversion and rainfall plus any changes in storage minus the water committed to downstream uses.

⁷ This approximately corresponds to the average 515 million m³ of annual diversion recorded over the period 1981-1999.

Depletion is thus maintained at previous levels (see Table 1) at the expense of drainage outflow and groundwater storage. This clearly shows that, under the simulated conditions, groundwater pumping – and, to a much lesser extent, drainage reuse – provide the flexibility required to maintain the overall water availability at a relatively constant level, thereby preventing important losses of production⁸. Deficit irrigation is however more generalized than before, which results in slightly higher values of water productivity.

Table 2 reveals a contrasted groundwater functioning between the two improvement scenarios. With the higher efficiencies introduced in the first scenario, the groundwater system is deprived of a large fraction of its recharge. Under these conditions, the recharge does not balance the pumping required to achieve the aforementioned flexibility. Consequently, pumping somehow takes place at the expense of the groundwater storage available for the next season. For example, the simulated 26 cm watertable fall is likely to result in a much lower than normal groundwater level in the beginning of the next year (the end of the simulation period approximately corresponds to the end of the rainfall season, and later possibilities for recharge are therefore very limited). In contrast, the ‘equity’ scenario supports a very dynamic functioning of the groundwater system, abundantly recharged by water transport and application inefficiencies, but also intensively solicited to buffer demand-supply gaps. Under similar conditions, the groundwater system can be managed as a real underground storage, the large capacity of which provides a maximum of flexibility for irrigation. This benefit however has an associated cost: the ‘equity’ scenario is more expensive, in terms of diversion and energy (pumping), than the ‘high efficiencies’ scenario. A trade-off thus appears between flexibility and energy, or alternatively between flexibility and irrigation costs. This trade-off might also extend to water quality, notably in the downstream divisions, where groundwater is of lesser quality.

Equity is another essential issue that deserves some additional comments. Although the ‘high efficiencies’ scenario achieves a slightly higher overall production than the ‘equity’ scenario, it does so in a much less equitable manner. This scenario actually disadvantages downstream divisions in a both direct and indirect way. The first, direct disadvantage relates to the defined upstream priority for main canal water allocation. The second disadvantage is a side effect of the former: downstream divisions are allocated less water in an ‘efficient’ canal system, which results in limited groundwater recharge, and thus limited potential for sustained groundwater use. Yet, it is precisely in such situations of unfair canal water allocation that groundwater is more critically needed downstream. Beyond the evident social benefits, Table 2 suggests that improving water allocation equity is also a way to raise water productivity in the study area.

⁸ It is interesting to note that vegetables and fruits, which represent the largest fraction of the total gross value of production, never get significantly water-stressed under the simulated conditions.

5. Concluding remarks

Irrigation models commonly focus on a limited portion of the water balance, missing important sources and uses of water within irrigation projects. For this particular reason, they are generally of limited value to manage irrigation water within the broader context of basin water resources. OASIS, a new irrigation model which integrates recycling and captures all the main factors of the water balance, was introduced in this paper. The main outcomes of the OASIS model application in the Bojili Irrigation District (BID), a large-scale irrigation scheme located in China's lower Yellow River basin, were also presented.

In spite of the numerous assumptions that had to be made to address large knowledge gaps, the nature of the BID scheme was probably well captured by the model. There is however a number of aspects that require further validation and more detailed investigations are recommended before any action is taken. Simulations revealed the high overall efficiency of the district and the very little remaining scope for water saving gains. This suggests that the major water conservation actions have already been taken in the district. The initial analysis undertaken showed that conventional water conservation measures, for instance canal lining, would not result in any significant water saving. Instead, such measures would deprive the groundwater aquifer of a significant fraction of its recharge, thereby hindering its longer-term capacity to mitigate scarce and poorly reliable canal supplies.

The ability of OASIS to integrate the surface water with the groundwater systems proved to be absolutely critical for the case of BID. Without properly accounting for the vertical capture and recycling of irrigation return flows, a model would indeed necessarily yield a very misleading picture of water use efficiency, productivity and equity in this irrigation district. The OASIS application in BID demonstrated the value of the model for an initial appraisal of irrigation interventions. Ultimately, this application suggests that OASIS's innovative skills can bring valuable support to identify opportunities and means to improve water use efficiency, productivity and equity in water-short areas such as the Yellow River basin.

Acknowledgements

Material was largely drawn from projects supported by the Swiss Agency for Development and Co-operation (SDC) and the European Union.

Bibliography

- Keller, A.A., and Keller, J. 1995. *Effective Efficiency: A Water Use Efficiency Concept for Allocating Freshwater Resources*. Discussion Paper 22. Center for Economic Policy Studies, Winrock International.
- Molden, D. 1997. *Accounting for water use and productivity*. SWIM Paper 1. Colombo, Sri Lanka: International Water Management Institute.
- Pereira, L. S., Musy, A., Cai, L.G., Lance, J.-M., Mao, Z., Zimmer, D., Schultz, B. and Tyagi, N.K. 2000. *Policies for irrigation water savings in the Yellow River basin*. S&T

Co-Operation with Asia in the Area of Sustainable Management of Natural Resources,
CEC-DGXII and P.R. China SSTC-DIC, Brussels, CD-ROM.

Roost, N. 2002. *Strategic Options Analysis in Surface Irrigation Systems: Integrated Modelling for Efficient, Productive and Equitable Water Use*. Ph.D. dissertation.
Lausanne, Switzerland: Swiss Federal Institute of Technology (EPFL).