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MULTI-CRITERIA ANALYSIS FOR IMPROVED WATER USE AND SAVING IN A LARGE SURFACE IRRIGATION DISTRICT

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SUMMARY - Water saving in irrigation is a main issue worldwide. This paper refers to a field and modelling study performed in a large surface irrigation system in the upper Yellow River Basin. The irrigation scheduling simulation model ISAREG was used to evaluate the current irrigation schedules and to generate improved ones. Capillary rise from the water table, deep percolation, leaching requirements and impacts of salinity in crop evapotranspiration, crop water stress and yields were considered. Field evaluations of farm irrigation systems were performed to parameterise the surface irrigation model SRFR, which was used to generate improved basin irrigation scenarios. Both models were explored interactively to create a complete set of demand scenarios used with the SEDAM model. SEDAM is a DSS tool that allows evaluating impacts of improvements in farm and off-farm irrigation canal systems. Irrigation scheduling improvements consist in reducing the number of irrigations and adopting new calendars in accordance with the water table depth and soil salinity. Surface irrigation improvements consist of improving land levelling and increasing the inflow rates by unit width. Water saving in paddy irrigation was considered through replacing the current deep flooding method by shallow water irrigation. All farm improvements must go together with lowering the water table, which is feasible when canal systems be modernised. This refers to an increased number of cross regulators, improvement of critical off-takes, and changing distribution and delivery rules. Results show that waterlogging and salinity may be controlled and water saving represent about 50% of current inflow volumes.

Keywords: Irrigation scheduling, basin irrigation, paddy rice irrigation, canal distribution systems, demand simulation, modelling, Yellow River.

RESUMÉ - L'épargne d'eau en irrigation est essentielle partout. Cet article concerne une étude de terrain et de modélisation pour un grand système d'irrigation de surface dans le bassin supérieur du Fleuve Jaune. Le logiciel ISAREG était utilisé pour évaluer les calendriers d'irrigation et produire d'autres améliorés. L'ascension capillaire, la percolation, les fractions de lessivage et les impacts de la salinité sur l'évapotranspiration et les rendements étaient considerés. Des évaluations de terrain ont servi à parâmetriser le modèle SRFR, lequel était utilisé pour construire des scénarios d'amélioration pour l'irrigation par bassins. Ces modèles étaient explorés interactivement pour créer la base de données des scénarios de demande utilisés par le SAD SEDAM pour l'évaluation des des améliorations des systèmes d'irrigation à la parcelle et de distribution. Les ameliorations des calendriers d'irrigation consistaient en reduire le nombre d'arrosages et à ajuster les doses aux conditions de la nappe phréatique et à la salinité. Les améliorations des systèmes par bassins concernaient l'adoption du nivellement de précision et l'augmentation des débits unitaires. Pour le riz, l'épargne concerne la substitution de l'innondation avec lâmes profondes par eaux basses. Toutes les améliorations à la parcelle recquièrent l'abaissement de la nappe, ce qui est faisable si le réseau par canaux est modernisé en améliorant les régulateurs de niveau d'eau, modifiant les prises sur canal et changeant le service de distribution. Les résultats montrent que les épargnes d'eau peuvent atteindre 50% des volumes d'irrigation actuels et l'engorgement et la salinité peuvent être controlés.

Mots-clés: calendriers d'arrosage, irrigation par bassins, rizières, systèmes de distribution par canal, simulation de la demande, modélisation, Fleuve Jaune.

INTRODUCTION

Water scarcity is among the main problems to be faced by many societies and the World in the XXI century. Water scarcity is commonly defined as a situation when water availability in a country or in a region is below 1000 m^3 per person per year. The threshold of 2000 m^3 per person per year is considered to indicate that a region is water stressed since under these conditions populations face very large problems when a drought occurs or when man-made shortages are created (Pereira *et al*., 2002).

Water scarcity causes enormous problems for the populations and societies. The lack of water does not allow industrial, urban and tourism development to proceed without restrictions on water uses and allocation policies for other user sectors, particularly agriculture. Natural fresh water bodies have limited capacity to respond to increased demands and to receive the pollutant charges of the effluents from expanding urban, industrial and agricultural uses. In regions of water scarcity the water resources are often degraded, or subjected to processes of degradation in both quantity and quality, which adds to the shortage of water. Health problems are commonly associated with scarcity, not only because the deterioration of the groundwater and surface waters favours water borne diseases, but because poverty makes it difficult to develop proper water distribution and sewerage systems. Water conflicts often arise in water stressed areas among local communities since sharing a very limited and essential resource is extremely difficult despite legal agreements. Poverty associated with water scarcity generates migratory fluxes of populations within countries or to other countries. Last, but not least, water for nature has become a low or very low priority in water stressed zones. Preserving natural ecosystems is often considered a superfluous use of water compared with other uses that directly relate to healthy human life, such as domestic and urban uses, or that may lead to the alleviation of poverty and hunger, such as uses in industry, energy and food production.

The Yellow River basin is typically an area facing water scarcity problems that severely impact irrigated agriculture. Water scarcity there is due to aridity, drought and man induced water shortage in relation to the ever-increased demand for urban and industrial water uses. Surface irrigation is used in almost 100% of the area using surface water conveyance and distribution facilities which constitute large or vary large irrigation districts. Thus, a case study relative to this basin is used to illustrate the use of several research tools, including multi-criteria analysis, aiming at finding improved irrigation practices and management for water saving in large surface irrigation districts.

THE STUDY AREA

The Yellow River basin is one of most populated areas in China, where about 130 million people, mostly farmers, live in dependence of this river. The Yellow River is the second largest river in China, its basin covers 752000 km^2 (Fig. 1), but water is very much charged with sediments, particularly during the monsoon rainy season, which highly reduces the water availability and requires special care in dam storage and diversion in the mid and lower reaches, where most of the population lives. Agriculture is the main water user (> 90%) whiles the domestic and industrial demands are growing very fast. The Yellow River Conservancy Commission (YRCC) and the Province Water Conservancy Services regulate water allocations to the Provinces and the main users, including the irrigation districts. Due to water scarcity and to the increased demand by the non-agricultural users, sustainable agricultural development is only possible if considerable water savings are attained (Cai *et al*., 2003).

A research project on policies for water savings was initiated in 1998 focusing on the sustainable use of water and soil resources in the Yellow River basin (Pereira *et al*., 2003b). Among the main objectives of this study are the identification of main water savings in irrigation and the definition of improved water management strategies. Two research areas were considered, one in the upper basin, the Huinong Irrigation District (HID) in the Ningxia Autonomous Region, which is focused in this paper, the other downstream, the Bojili Irrigation District in the Shandong Province (Fig. 1). The HID is part of the Qingtongxia system, located in the northern part of Ningxia Province, on the east bank of the Yellow River. The Qingtongxia system has a total irrigated area of 330 000 ha, while the Huinong Canal supplies about 75 000 ha. Management of the HID is performed through 8 Divisions, which adopt independent allocation decisions.

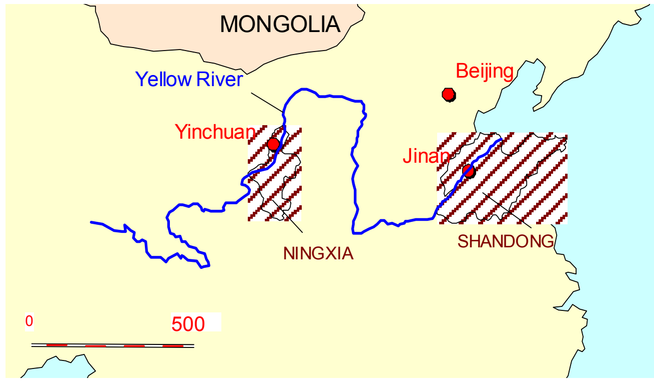


Fig. 1. The Yellow River Basin and location of study areas.

The climate is arid, with an average 190 mm rainfall, hot summer and cold winter. The cropping systems are based on irrigated wheat and maize, more often intercropped, and paddy rice. Water logging and salinity occur in large areas due to excess water diverted into the irrigation system, which constitutes a quite common contradiction with the water scarcity prevailing in the basin. Water diversions represents more than the double of the irrigation requirements, from which near one third is drained back to the river; the remaining seeps and percolates to the groundwater, thus creating water logging and salinity built-up. At present, the water-table is near 0.5 m depth during most of crop season. Soils are alluvial, silty clays to silty sands. Saline soils are not cropped while waterlogged less saline lands have reduced yields. An extensive drainage network exists but it has no capacity to drain the excess water into the canal system; however, it may function appropriately if water diversions into the irrigation system are controlled (Hollanders *et al*., 2003).

MODELLING

Research focused the farm irrigation, the conveyance and distribution canal systems and the drainage system (Pereira et al., 2003b). The drainage conditions and its improvement were the object of a specific study (Hollanders et al., 2003). Computer modelling has been utilized for irrigation scheduling because this easy allows developing and evaluating alternative strategies (Pereira et al., 1995); models have been calibrated and validated before being explored (Liu et al., 1998, Liu et al., 2000). Field evaluations and modelling were used for assessing the present situation on farm irrigation performances of upland crops, wheat and maize, and generating alternatives for surface irrigation improvement. Field research was adopted to assess present and improved paddy rice irrigation (Mao et al., 2004).

Modelling the demand and delivery with the SEDAM model (Gonçalves et al., 2003) uses an up-scaling approach, starting at the downstream units served by the distributor channels and ditches, and aggregating the demand to the sub-branch and branch canals and, finally, to the sector. The demand at the unit is generated from using interactively the irrigation scheduling and the surface irrigation simulation models, as well as data relative to the paddies. Results of SEDAM simulations constitute input data for a supply system DSS model (Roost et al., 2003, Roost and Musy, 2004). An interactive exploration of both models was tested.

Farm irrigation

The ISAREG model (Teixeira and Pereira, 1992), was selected to evaluate and support improved irrigation scheduling because its simplicity and accuracy were demonstrated in others applications in North China (Liu et al., 1998, Liu and Fernando, 1998). The model uses the methodologies proposed in FAO 56 Manual (Allen et al., 1998), which are proved for North China, both relative to FAO Penman-Monteith reference evapotranspiration ETo (mm/day) and to crop coefficients (Liu and Pereira, 2000; Pereira et al., 2003a).

The ISAREG model has been improved to accurately compute the capillary rise into the root zone from a shallow groundwater table and to estimate the percolation water volumes (Fernando *et al.,* 2001; Liu *et al.*, 2001). It was improved further to predict crop evapotranspiration as affected by soil salinity and to compute the leaching requirements (Campos *et al.*, 2003; Pereira *et al.*, 2004). It used locally collected meteorological, crop and soil data to evaluate the actual irrigation schedules used for the main crops in the area and to support the search for improved irrigation schedules which could contribute to control the waterlogging and salinity problems occurring in HID. These improved schedules are considered in the analysis of actual performances of the farm irrigation systems and in the search for improved solutions for these basin systems.

The improvement of basin irrigation systems requires that appropriate field data be collected to characterise the farm systems and the respective performance. Field evaluations of actual irrigation events are therefore required. The methodology for these evaluations is well proved (e.g. Walker and Skogerboe, 1987) including in China (Li and Calejo, 1998). When field data are available, simulation models can be used to obtain the optimal estimates of the hydraulic roughness and infiltration parameters, and later to design the improved systems. The surface irrigation simulation model SRFR (Strelkoff, 1993) was used iteratively to optimise the infiltration and roughness parameters using data from both infiltrometer tests and field evaluations in farmers fields in Pingluo (HID) using a methodology previously proved for North China (Li and Calejo, 1998). SRFR and SIRMOD (ISED, 1989) models were used to generate the improved solutions for basin irrigation. Further details are given by Fabião *et al.* (2003) and Pereira *et al.* (2004).

Demand and delivery simulation

The irrigation system has the following components (Fig. 2): (a) the farm irrigated fields, (b) the unit irrigated area, which is the area supplied by a distributor comprising a variable number of fields, (c) the sub-sector, which is the area served by a branch and several sub-branch canals that supply a variable number of distributors, (d) the sector, grouping the areas served by several branch canals, located either on the left or the right side of the main canal, and (e) the division, which is the command area located between two major hydraulic structures in the main canal where discharges are measured. The divisions have independent management and are generally divided into two sectors, on the left and right sides of the main canal.

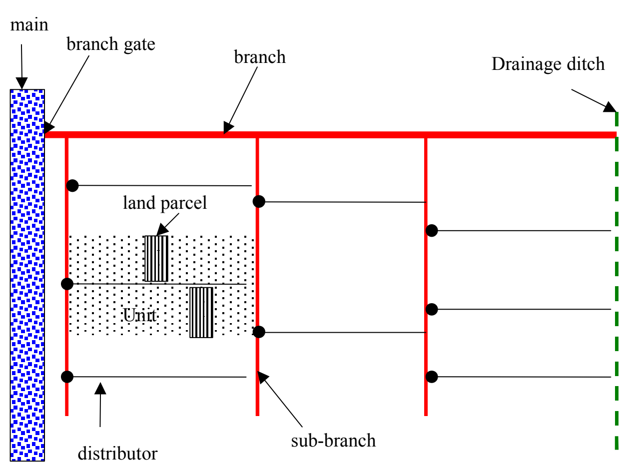


Fig. 2. Schematic representation of a distribution sub-sector network.

Because fields are too small, averaging 0.1 ha, the first level for demand estimation and simulation is the unit, which area ranges from 2 to 6 ha. This requires the assumption that all fields in the same unit have the same crop, irrigation schedules, soil water holding capacity and infiltration, groundwater depth and salinity conditions. The demand at the unit scale is built from results of the irrigation scheduling simulation model ISAREG and the surface irrigation simulation models SIRMOD and SRFR. The first generates the irrigation dates, depths, and impacts on yields, and the second produce the time duration of the irrigation and the respective performance indicators. A simplified procedure using the paddy fields experimental data (Mao *et al*., 2004) is developed to simulate the demand for the units cropped with rice. The demand by each unit - discharge rate, duration and timing of deliveries - is then aggregated with those of other units supplied by the same sub-branch canal and then to the area served by the corresponding branch canal, so yielding the sub-sector demand (Fig. 3). Finally, the generated sub-sector demands are aggregated at the sector and the division scale.

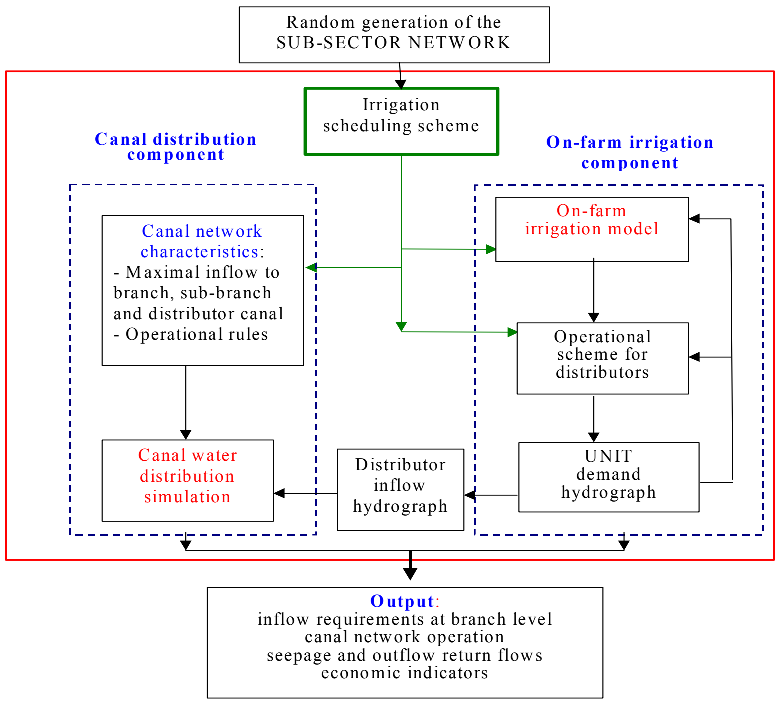


Fig. 3. Schema and components of SEDAM model.

The available data describing the irrigation network system is rather scarce and not appropriate for use with a GIS. Data on soils is from observations in few locations within the HID. Information on crops refers to their percent distribution at county level. The percent distribution of groundwater depths and salinity has been estimated at the division scale. The characteristics of each sector are partially known: command area and number, length and maximal discharges of the branch canals. However, only typified data are available for the number, length, size, discharges and area served by the sub-branches. Similarly, only typified data can be used to characterize the number, length, size and discharge of tertiary distributors, so the size and field characteristics of the units. The SEDAM model therefore adopts a random procedure to generate the data relative to sub-branches, tertiary distributors and units that are required for the demand and delivery simulation. The actual distribution (% of area) of soil types (water holding capacity), soil infiltration, groundwater depths and salinity in each sector are used to randomly assign these data to the different branches in a sector. The actual distribution (%) of crops and respective irrigation methods - basin irrigation for upland crops and flooding irrigation for paddy rice - are randomly assigned to the sub-branches.

The characteristics of the fields in the units are set by randomly generation using typical data on field lengths, widths and slopes. The ratio between actual average sector inflow discharge and the branch design discharges of the sector is used to estimate the available branch canals discharges. The typical ratio discharge-area served is used to generate the actual discharges at the sub-branch canals. The typical area-length ratios are adopted to generate data on sub-branches. A control is used to verify if the sum of areas and discharges generated are close to the actual ones. When this is not verified, the procedures are repeated.

The assumptions made do not allow assigning results of simulations to a specific sub-branch or branch canal as e.g. model CADSM (Walker at al., 1995) does, but allow simulating the functioning of the distribution system corresponding to the sector scale where the supply is currently known. Therefore, the model could be calibrated and validated by comparing the actual 10-day supply to the sectors and divisions with the model generated demand under the present conditions. After calibration, the model is able to support the evaluation of the impacts due to alternative improvements in the farm systems (e.g. irrigation schedules, inflow rates, land levelling) and in canal system management. Results from simulations may help to establish new delivery schedules but not to produce real time management rules for the distribution system.

The simulation of the demand at the unit scale requires various steps (Fig. 4):

- The inflow rates into the distributors served by any sub-branch canal are randomly generated taking into consideration the area irrigated and the probability of occurrence of discharges. The inflow rates to the tertiary distributors (Q_T, l/s) are adjusted considering the typified data on the number of distributors operating simultaneously.

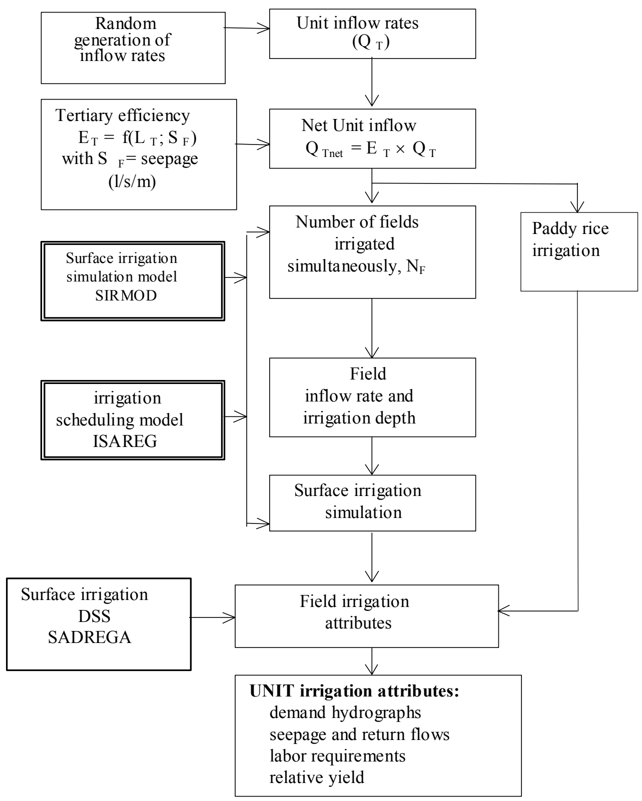


Fig. 4. Schema of the demand and delivery simulation at the unit scale.

- The seepage volumes are estimated from an efficiency ratio for the tertiary distributors (Ef_T), which is estimated as a function of the tertiary length L_T (m) and a seepage factor S_F (l/s/m) referred to the unit length of the tertiary canals (Li *et al*., 2003). The net unit inflow rate is then $Q'_T= Ef_T\ Q_T$ (l/s).
- The inflow discharge at the field level q_F (l/s) is randomly generated from the observed probabilities of occurrence of field inflow discharges, which allows to estimate the number of fields irrigated simultaneously, N_F=INT(Q'_T/q_F). Therefore, computations at field level are performed using the adjusted discharge $q'_F = Q'_T/N_F$.
- The ISAREG model computes an irrigation schedule for each combination climate - soil - groundwater depth - salinity - crop, i.e. the irrigation timings and depths (D, mm). These data are

used with SIRMOD or SRFR for each combination soil infiltration - groundwater depth - field length - field width - inflow rate to determine the time duration of the irrigation, t_i. These models run for typical data sets and produce a database. SEDAM reads the database and interpolates the data according the field characteristics considered.

- The same field simulation models create the field irrigation attributes that are also stored in the database. SEDAM reads it, interpolates the values and, then, creates the unit irrigation attributes (Fig. 4). These attributes include the demand hydrographs, percolation and runoff return flows, labour requirements and relative yield losses, which are further used to evaluate the scenarios for improvement as described in the last section of the paper.

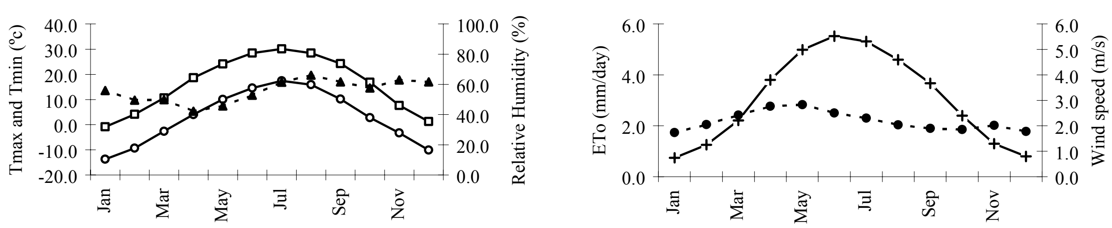
At present, the farmers using water from any distributor order water to the branch canal manager, who then asks a given inflow rate and daily time allocation to the Division Authority. The latter decides the allocation of a certain inflow rate during a full day for each canal branch, whose decisions aim at minimizing the number of days in each 10-day period where any branch canal is supplied. When knowing that water will be delivered to the branch canal, the farmers plan the water distribution adjusting the inflow rates to tertiary distributors and fields, and application times. However, irrigation is practiced during the daytime period only, thus during the night period the water flows through canals and distributors as runoff return flow to the drainage ditches. Farmers may do not be able to irrigate during the period of delivery, but have the opportunity to irrigate in a later day. This non-used water adds to runoff.

The practices referred above are considered to establish the procedures adopted for simulation as described by Gonçalves et al. (2003). These include the priority given to irrigation of paddies, irrigation times, order of units' irrigation among others.

ASSESSMENT OF PRESENT SITUATION

Irrigation scheduling

The model ISAREG was primly applied to climate data relative to Pingluo (latitude: 38º55'N, longitude: 106º33'E, elevation: 1099 m). Climate in the Huinong area is arid, with hot summer and very cold winter (Fig. 5), where annual rainfall averages 190 mm.



a) b)

Fig. 5. (a) average minimum (–o–) and maximum temperature (–□–) and relative humidity (--▲--); (b) average wind speed (--●--) and reference evapotranspiration (—+—) at Pingluo (1988-99).

The classes of the total available soil water (TAW) at HID were defined from the analysis of the observed soil hydraulic properties data. Three classes were retained respecting to TAW equal to 320, 280 and 240 mm/m approximately. In HID, the high groundwater levels limit root depth to 0.5 m and impact the contribution to crop requirements, infiltration conditions at irrigation and cause water logging and salinity problems.

The main crops are rice, wheat and maize. The later are often intercropped to make better use of the land and energy available. Other crops are pulses and horticultural crops but in a proportion negligible relative to the cereal crops. A winter irrigation is applied by November, before soil freezes, to all crops. Wheat is planted after melting of soil water, and maize is planted after wheat gets 2 to 3 leaves, attaining full development after wheat harvesting. Rice is planted by May.

The crop coefficients and the water depletion fractions for no stress were estimated using the methodology proposed by FAO (Allen et al., 1998), well proved for North China (Liu and Fernando, 1998; Liu and Pereira, 2000). A specific approach was used for wheat-maize intercropped (Campos et al., 2003).

Simulations for wheat, maize, and wheat-maize intercropped were performed with the available monthly weather data sets relative to five county weather stations. Relatively small variations were observed both in time and space (Campos et al., 2003). The year 1993-94 was selected as reference for the modelling studies since water supply data were available for that year and could therefore be used to validate the demand and supply models. Using daily weather data for Pingluo (1993-94) and the current water table depth, simulations were performed for all TAW soil classes and the main crops adopting the average irrigation depths and frequency actually applied as observed in farmer's fields. Due to the water table influence, computations were performed for a root zone limited to 0.5 m. Results for a soil having TAW = 281 mm/m are shown in Table 1.

Table 1. ISAREG simulation of the current average irrigation schedules at Pingluo (HID) with the present water table and a soil TAW = 281 mm/m when season rainfall was 130 mm

Crop	Irrigations after planting	Season irrigation (mm)	Deep percolation (mm)	GW (mm)	ETc_{adj} (mm)	ETc (mm)
Intercrop	6	630	386	471	810	816
Wheat	4	422	213	297	546	554
Maize	5	521	266	383	747	780

A pre-planting irrigation, by November, provides water to the early stages of the crops and improves the physical conditions of these silty soils due to fine cracks created along the soil profile due to successive freezing and melting of the applied water. This irrigation is not included in Table 1 but the available soil water at planting is computed by simulating a bare soil condition from that winter irrigation to the planting date.

The consequences due to the very high water-table are well evident (Table 1): near 51 to 61 % of the applied depths turn into percolation to the groundwater, so contributing to maintain unfavourable water-table conditions, but 51 to 58 % of the crop water requirements are satisfied by the capillary rise fluxes (GW). Due to this unbalanced situation, the actual ET (ETc_{adj}) is below the maximal crop ET (ETc), and yields are affected.

Basin irrigation

Field evaluations have been performed in Pingluo (HID) and in Huimin and Wudi (BID). The basin geometry observed consists of the basin length, width and micro-topography. The micro-topography is described by the average slope, S0 (m m-1), and by the indicator Δy (m m-1), which describes the uneven surface conditions in the field (Li and Calejo, 1998). The main results concerning the field geometry are presented in Table 2. They show that basins are of wide rectangular form and the slope is non-uniform.

Table 2. Observed basin lengths, widths, slopes S_0 and non-uniformity Δy.

	Length (m)	Width (m)	S_0 (‰)	Δy (%)
Average	37.9	29.0	0.90	0.039
Maximum	46.5	31.9	2.50	0.077
Minimum	24.7	22.6	0.20	0.018
Standard deviation	7.3	2.9	0.70	0.024

The average inflow rates vary from 0.8 to 1.2 l s-1 m-1, respectively at the last and the first irrigation, and have a coefficient of variation from 0.12 to 0.41. Thus, they have small variations from the first to the last irrigation, but average discharges are in general small, which largely contributes to long advance times and, therefore, to excessive supply times and over-irrigation.

Simulations of field tests with the SRFR simulation model were applied in the inverse solution of the surface irrigation problem to search the infiltration and roughness parameters using advance and recession observation data (Katopodes *et al*., 1990). However, because the high level of the water-table highly impacts infiltration during the recession phase, two sets of parameters were obtained, one relative to present conditions, the other for the target water-table as described by Fabião *et al*. (2003). Therefore, two sets of parameters for each of the six currently practiced irrigations were obtained. Later, based on observations in several locations in HID, three types of infiltration soils were defined (Fabião *et al*., 2003).

The analysis of the actual irrigation performances was done with the SRFR model using field evaluations data and considering the infiltration depth required, Zreq (mm), computed with the ISAREG model for Pingluo daily data and the actual water table depths. The computed values for Zreq are shown in Table 3, where they are compared with the observed average depths applied D (mm). The large differences between Zreq and D reflect the influence of the capillary fluxes from the very high water table.

Table 3. Ranges of irrigation performances evaluated in farmers fields at Pingluo.

Irrigation number	q ($l\ s^{-1}\ m^{-1}$)	D (mm)	Zreq (mm)	E_a (%)	DU_{lq} (%)	Percolation (mm)
1^{st}	1.0 - 1.4	107 - 109	92	77.8 - 85.9	61.4 - 90.9	15 - 24
2^{nd}	0.7 - 1.3	90 - 136	30	22.0 - 33.5	56.8 - 95.6	64 - 106
3^{rd}	0.4 - 0.9	94 . 114	51	44.8 - 54.4	82.9 – 87.3	43 - 63
4^{th}		111	17			
5^{th}	1.2	105 - 157	50	25.6 - 35.2	84.4 - 92.7	12 - 77
6^{th}	0.7 - 0.9	97 - 141	14	9.9 - 14.4	99.3 - 94.3	83 - 127

Results for the actual irrigation performances in HID are shown in Table 3, including the distribution uniformity, DU_{lq} (%), and the application efficiency, E_a (%), as defined by Pereira and Trout (1999), as well as the percolation volumes. Results show that DU_{lq} are generally high but E_a are very low due to the negative impacts of the high water table. Since basins are fully diked and runoff does not occurs, all excess water percolates to the water table, thus helping to keep existing unfavourable conditions. Therefore, in building improved scenarios, the control of water table is considered an essential pre-condition.

Irrigation demand and delivery

The analysis of present demand and delivery conditions focus the Divisions 2 and 4 in HID. Results from the application of the SEDAM model to both Divisions are shown in Fig. 6. Results concern the 10-day recorded supply, simulated delivery, simulated (aggregated) demand at farm level, and the simulated (aggregated) water consumed at farm level for the year 1994.

Results show that the model could approximate the simulated delivery to the recorded supply for both Divisions. However, there are discrepancies but the total volumes recorded and simulated are similar. Results evidence that volumes supplied were much higher than the aggregated farm demand, i.e., the water volumes required to perform the irrigation as it is currently practiced. Differences between the simulated delivery and the farm aggregated demand represent runoff and seepage in the canal systems, while the differences between the farm demand and the farm consumption correspond to field percolation, which represent more than 50% of the supplied volumes, as analysed in Fig. 7.

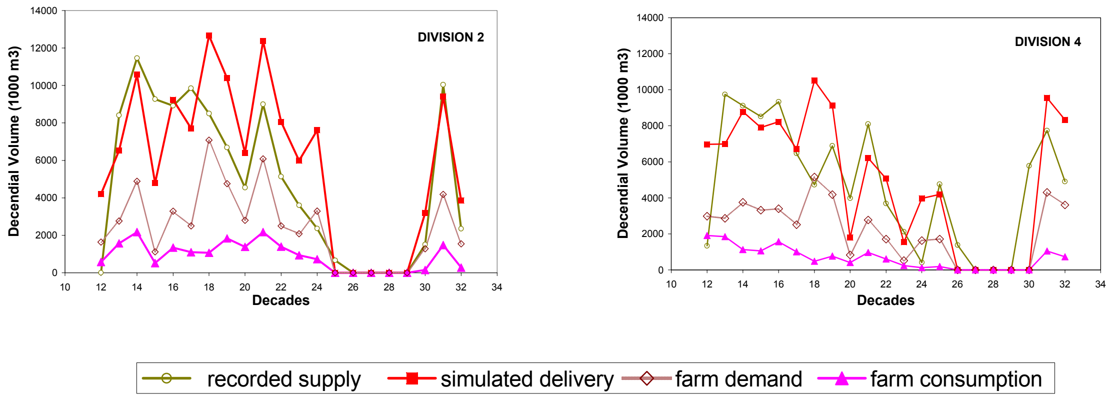


Fig. 6. Comparing the 10-day recorded supply with the SEDAM simulated delivery farm water use and consumption for Division 2 and 4 of HID.

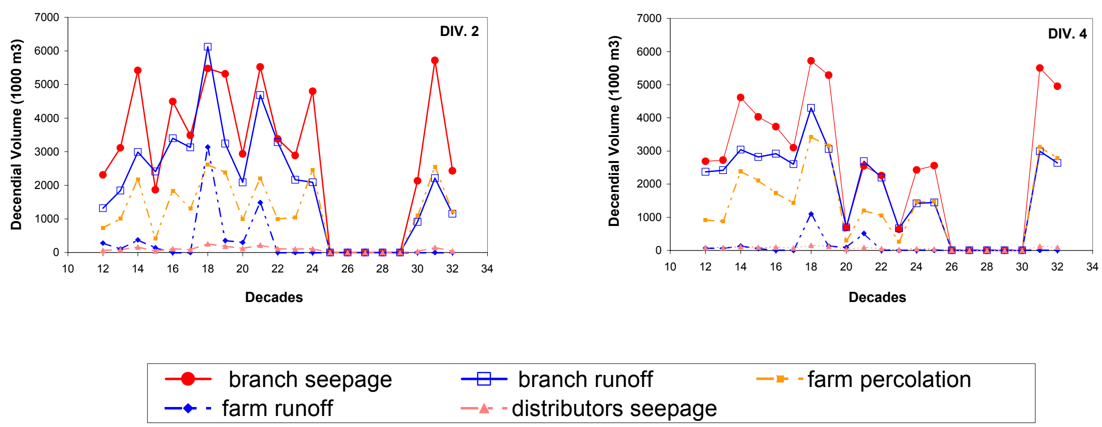


Fig. 7. Simulated seepage and runoff in branch and sub-branch canals, compared with percolation and runoff at farm level, and seepage in the distributors for Division 2 and 4.

Operational losses in the branch and sub-branch canals by far exceed those at the distributors and farm systems (Fig. 7). Simulated seepage and runoff are of the same order of magnitude. High seepage is due to the fact that canals are not lined, they are often cleaned from the large amount of sediments carried with the Yellow River water that deposit each time they operate, and to high water levels adopted for their operation because off-takes structures require high water levels in the canals. Studies on groundwater and drainage (Hollanders *et al.*, 2003) clearly show a nearly steady state flow from the irrigation canals to the drainage canals. Runoff volumes are very high because branch canals and most of sub-branch canals are operating for 24 hours but water is often not used for more than day-time, i.e. 16 - 18 hours. Discharges during the night–time are added to runoff into the drainage system, as well as excess water during day–time. Thus, the drainage system is generally full, with the water level often higher than the surrounding land.

At farm level, deep percolation is the main operational loss, from both upland crop basins and paddies. Farm runoff is mainly produced from the paddy rice basins because basin dykes are too small and water levels are excessive (Mao *et al.*, 2004).

SIMULATION OF IMPROVED FARM IRRIGATION SCENARIOS

Irrigation scheduling

Simulations developed through a parallel study (Hollanders *et al*., 2003) led to formulate an improved and feasible scenario for the water table. This target scenario corresponds to maintain the groundwater table at approximately 1 m depth, allowing 0.9 m root depth, and helping to avoid most of current waterlogging and salinity related problems.

Improved irrigation schedules are designed under three main objectives: water saving, control of percolation and application of a leaching fraction according to the soil salinity. For soils with low salinity, leaching is assumed to be performed through the winter irrigation only and there is the need to control, hopefully to avoid percolation through the root zone boundary. Therefore, it is required to modify the irrigation scheduling by reducing the number of irrigations and changing the irrigations volumes applied. Simulations were performed for the three TAW soil classes and for different number of irrigations. Results exemplified in Table 4, when appropriate irrigation depths and timings are selected and basins are zero levelled, show that the season irrigation depth is reduced and deep percolation is controlled.

Table 4. Simulations of improved irrigation schedules at Pingluo for the target water table depth, zero levelled basins and a non-saline soil with TAW=281 mm/m.

Crop	Irrigations after planting	Season irrigation (mm)	GW (mm)	ETc_{adj} (mm)	ETc (mm)
Intercrop	5	550	65	817	817
Wheat	4	403	21	554	554
Maize	4	440	58	755	755

For saline soils, a leaching fraction up to 10 % is required. Two different scenarios were then considered:

a) soil ECe = 3 dS/m, thus when $ECe > ECe_{threshold\ maize}$ but $ECe < ECe_{threshold\ wheat}$ thus causing a maize yield decrease near 20 % but not affecting wheat yields;
b) soil ECe = 11 dS/m, i.e. $ECe > ECe_{threshold\ wheat}$ that produces an average wheat yield decrease near 20 % and heavily impacts maize yields, so this crop is not considered.

The respective simulation results for zero levelled basins aiming at maximizing yields, i.e. when ETc_{adj} = ETc, are summarized in Table 5. The results show that the number of irrigations and the applied season depth can be reduced relative to the present situation (Table 1) and allow the application of a leaching fraction at every irrigation event.

Table 5. Improved irrigation schedules for saline soils in zero levelled basins aiming at maximizing yields (TAW = 281 mm/m, 130 mm rainfall during the crop season).

Crop	Irrigations after planting	Season irrigation (mm)	EC_e (dS/m)	Leaching (mm)	GW (mm)	ETc_{adj} (mm)	ETc (mm)
Intercrop	4	490	3	39	88	817	817
Wheat	4	482	11	44	3	554	554
Maize	5	600	3	50	7	755	755

Further reductions in applications depths and a reduced number of irrigation events are also possible with a light decrease in crop ET (Campos *et al*., 2003). These results show that large improvements in irrigation management are attainable if the water table depth is lowered, basin land levelling and management are improved, and irrigation depths are timely applied.

Basin irrigation systems

A simulation analysis of irrigation performances was first developed considering the actual fields referred in Table 3 without improving the respective micro-topography. The target application depths Z_{req} were computed with the irrigation scheduling model ISAREG assuming that the groundwater table would be lowered to 1.0 m. This improved schedule requires only 5 irrigations instead of present 6. Simulations were performed for the most frequent soil types, including the application of appropriate leaching fractions. Several inflow rates were considered. Results show that the uniformity DU_{lq} would average 76 %, the application efficiency E_a would increase to about 65 %, but the percolation was still excessive (averaging 62 mm) due to the uneven slope of the field, which causes the advance to be slow and the application times to be excessive, thus the application depths largely higher then the required ones (Fabião *et al.*, 2003). Therefore, precision levelling for zero slope basins needs to be considered.

Simulations were then performed for Zreq and D computed to minimize percolation under various soil salinity conditions. Results in Table 6 for the field B1 and a non-saline soil show that very high distribution uniformity DU_{lq} and application efficiency (E_a), together with very low percolation, may be achieved when precision zero levelling is considered.

Table 6. Simulated irrigation performances for the intercrop, considering the target water table depth and precision zero levelling for a field length of 48m, and non-saline soils.

Irrigation number	q ($l\ s^{-1}\ m^{-1}$)	D (mm)	Z_{lq} (mm)	E_a (%)	DU_{lq} (%)	Percolation (mm)
1st	1	130	112.0	84.3	75	20.4
	2	118	109.5	93.3	90	7.7
	3	113	106.9	97.0	93	3.2
2nd	1	123	110.3	89.5	85	12.9
	2	115	109.1	95.4	93	5.2
	3	113	108.3	97.4	95	2.9
3rd	1	119	108.2	92.1	88	9.3
	2	115	109.7	95.4	94	5.1
	3	111	106.7	98.5	95	1.5
4th	1	119	109.7	92.3	93	9.0
	2	114	109.0	96.4	96	4.0
	3	113	109.0	97.5	97	2.7
5	1	120	110.5	91.4	92	10.2
	2	112	107.5	97.1	95	3.1
	3	112	108.5	97.4	96	2.8

Together with precision zero levelling, inflow rates play a major role in improving the distribution uniformity DU_{lq} and the application efficiency E_a, as well as for controlling the percolation as shown in Table 6. This is due to the fact that higher inflow rates produce smaller advance times which lead to more uniform infiltration. Therefore, when higher inflow rates are applied the percolation depths become smaller and the infiltration is more uniform along the field. Similar results were obtained for saline soils (Fabião *et al.*, 2003).

Precision zero levelled basins are the most appropriate to be implemented in the area for water savings, controlling percolation into the groundwater, and application of the leaching fractions. Moreover, zero levelled basins have the highest potential to contribute for controlling the water-table at its target level.

IMPROVED IRRIGATION DEMAND AND DELIVERY SCENARIOS

Identification of improved scenarios

Improved scenarios for water savings and improved crop conditions were developed in agreement with the decision making process summarized in Table 7. This process considers two scales, the farm and the delivery system, thus different decision makers and respective objectives, design and decision variables, and constraints. The design variables summarized in Table 8 refer to design and management parameters to be used in demand and delivery simulation of farm and delivery systems.

Table 7. Decision making process for improved irrigation and water saving.

	Decision making scales	
	Farm system	Delivery system
Objectives	▪ minimizing cost ▪ maximizing yield ▪ maximizing benefits ▪ minimizing salinisation ▪ maximizing water savings	▪ minimizing cost ▪ maximizing yield & benefits ▪ minimizing impact on drainage system ▪ maximizing social benefits (employment[(1)] and farmers income)
Decision variables	A- field inflow B- field irrigation scheduling C- field levelling D- field rice intensity I- salinity control	E- delivery refusal F- delivery branch lining G- delivery schedule H- delivery night runoff I- salinity control
Constraints	▪ water cost ▪ land cultivated area ▪ land taxes ▪ agronomic field practices	▪ canal system network ▪ maximum inlet discharge

(1) Objective considered at level of the area of influence of a township

Table 8. Decision variables to build up alternative improvement scenarios

Decision variables		Level of change
A	field inflow rate	A1= present (0,5 up to 3 l/s/m) A2= optimal $Q=f(L,S_0,Inf,n)$
B	field irrigation scheduling	B1= present B2= improved, with LF at every irrigation B3= improved, with LF at winter irrigation only
C	field land levelling	C1= present C2= $S_0 \leq 0,1$ % C3= zero levelled
D	field rice intensity	D1= present crop pattern D2= rice area reduced by 50% D3= rice replaced by other crops
E	delivery refusal	E1= present E2= reduced by 50%
F	delivery branch lining	F1= present, unlined canals F2= lined branch canals
G	delivery schedule	G1= random G2= rotation among sub-branches
H	delivery night runoff	H1= supply 24h/day H2= supply 21h/day H3= supply 18h/day
I	soil salinity	I1= present I2= improved to allow cropping I3= improved to reduce salinity impacts

The scenarios are built by combining in different ways the variables defined in Table 9. The present condition corresponds to the combination where all variables are at the level 1. The scenarios for simulation are built from these ones by assuming that improvements would be implemented progressively, only in part of the area in each sector and division (Table 10).

Table 9. Improvement scenarios.

Scenarios	A	B	C	D	E	F	G	H	I	Scenario strategy
I	1	2	1	1	2	1	2	1	1	Limited but easy to implement improvements at farm and delivery systems
II	2	2	2	1	2	1	2	2	1	Improvements focusing the farm system but limited regarding delivery management
III	2	2	3	2	2	1	2	3	2	More stringent improvements at the farm and off-farm
IV	2	3	3	3	2	2	2	3	3	Highest level of improvements

Table 10. Simulation scenarios considering a progressive implementation of the improvement scenarios.

Simulation scenarios	Percentage area in Sector/Division where implementing the improvement scenarios				Implementation time (years)
	I	II	III	IV	
1	100	0	0	0	1
2	50	40	10	0	2
3	20	40	30	10	3
4	0	50	40	10	4
5	0	30	50	20	5
6	0	20	50	30	6
7	0	10	50	40	7,8
8	0	0	50	50	9,10

However, the effective application of these scenarios implies changes in the supply system such as the regulation and control structures and off-take structures that regulate the supply to the branches, both in terms of water levels and diversion discharges (Roost *et al.*, 2003).

Multi-criteria analysis

The evaluation of the results of the simulations for the 8 scenarios in Table 10 is performed with the help of several indicators. The multi-criteria analysis is performed by considering three groups of criteria (Table 11): the expected benefits to the farmers, the foreseen costs for the farmers and the Irrigation District, and the environmental benefits due to water savings.

Table 11. Multi-criteria analysis.

Criteria	Attributes	Units
Benefits	1 - farm gross margin	Yuan/ha
Cost	2 - farm total water cost	Yuan/ha
	3 - delivery cost	Yuan/ha
	4 - drainage cost	Yuan/ha
Environmental impacts	5 - water use	m^3/ha
	6 - farm water seepage and runoff	m^3/ha
	7 - delivery water seepage and runoff	m^3/ha

The utility functions relative to the criteria in Table 11 are:

(1) Benefits criteria (j=1): $U_1 = \alpha_M \cdot X_1$

(2) Cost criteria (j=2,3,4): $U_j = 1 - \alpha_M \cdot X_j$

(3) Environmental criteria (j=5,6,7): $U_j = 1 - \alpha_W \cdot X_j$

where

$\alpha_M =$ 1.0E-4 (U_j=0 <=> Cost X_j=10000 Yuan/ha, j=1,2,3,4)

$\alpha_W =$ 3.33E-5 (U_j=0 <=> water volume X_j=30000 m^3/ha, j=5,6,7)

Adopting user defined weights (λ_j) for every criteria j, a global utility value is computed

$$U = \sum_{j=1}^{5} \lambda_j \cdot U_j$$

In this application the scenarios are ranked according the global utility values.

Improved scenarios: utility values and water saving

The 10-day recorded supply volumes for Divisions 2 and 4 are compared in Fig. 8 with the simulated results for scenario 4 (Table 10) relative to the delivery, farm water use and farm consumptive use. For this scenario, the foreseen aggregated delivery is reduced to less than 50% of the present supply volumes but farm consumptive use increases. The reduction in delivered volumes is mainly due to the reduction in branch seepage and runoff and in farm percolation. The increase in consumptive use relates to higher evapotranspiration due to improved cropping and yield conditions, namely those due to improved water table depths.

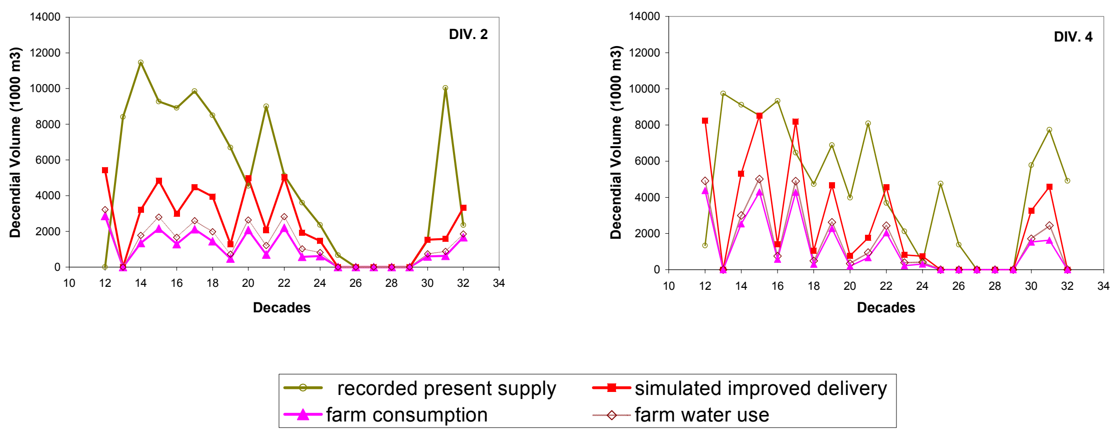


Fig. 8. Comparing the 10-day simulated delivery, farm water use and farm consumptive use relative to the improvement scenario 4 with the present recorded supply volumes for Divisions 2 and 4.

The reduction in operational losses is quite evident when comparing results in Fig. 9 with those for present (Fig. 8), corresponding to a reduction of 80 to 90% relative to the current situation.

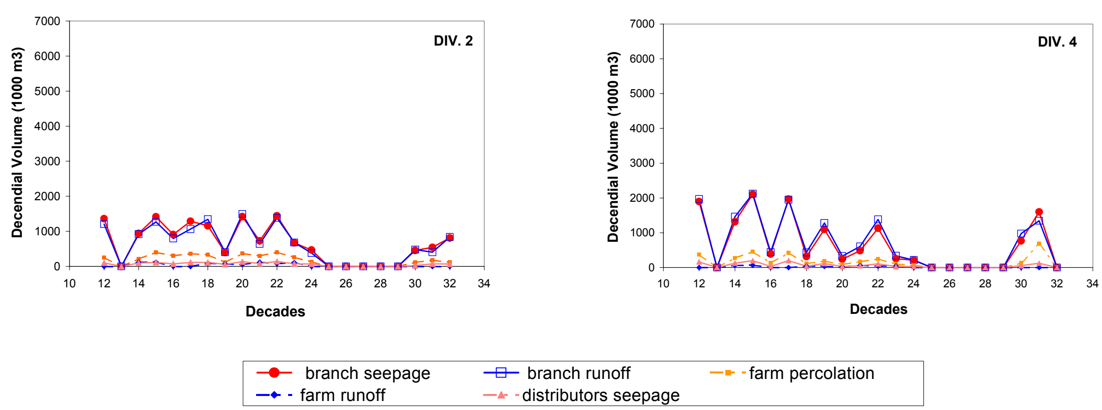


Fig. 9. Simulated branch canal seepage and runoff, distributors seepage, and farm percolation and runoff for Divisions 2 and 4.

Results from the multi-criteria analysis relative to the utility values for the 8 scenarios (Table 10) are given in Fig. 10. The utility value for the drainage cost do not change from scenarios 1 to 8 because drainage improvements are considered at the first stage of improvement activities. The utility value relative to farm water costs is also almost invariable because the impacts of water costs on the production costs are quite small. Diversely, the utility relative to delivery costs changes, denoting the related increased costs when system improvements are considered. The environmental benefits utilities show evident improvements from scenarios 0 to 8, particularly concerning the control of seepage and runoff, and the water saving. The farm benefits grow steadily but few from the present to the most improved scenario. This very low rate of increase reflects the structure of production costs and benefits in a peasant farming society. The global utility also increases, but with a relatively small rate from scenario 3 to 8. These results show that more costly improvements representing high technological solutions may do not be appropriate in a peasants society.

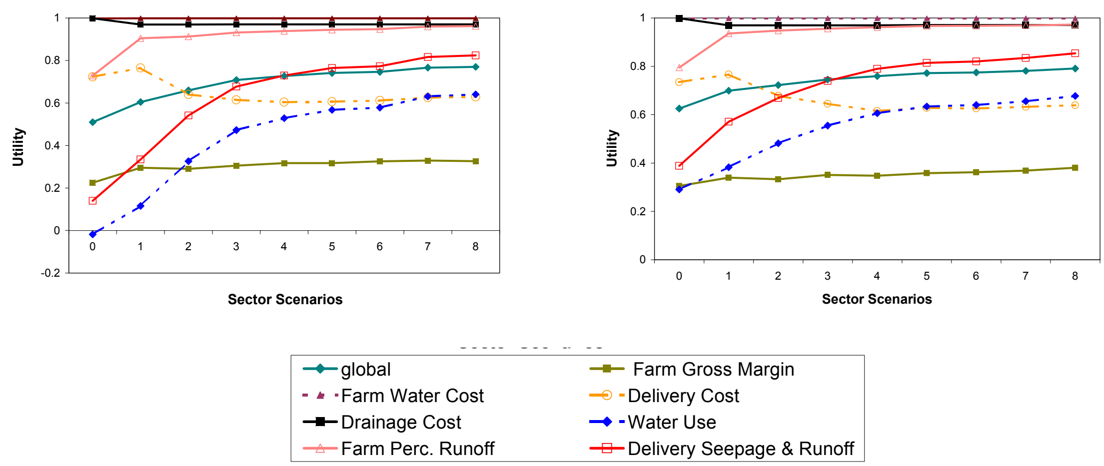


Fig. 10. The utility values for the current scenario (0) and the improved scenarios (1 to 8), Divisions 2 and 4 (respectively at left and right).

Since water saving is the main objective of this study, the impacts of the scenarios assuming their implementation during 10 years (Table 10) are shown in Fig. 11. It can be seen that the total water use could be reduced from more than 3000 mm at present to about half in 3 years and to near 1000 mm in 10 years in case of Division 2. At same time, seepage and percolation could reduce from more than 2500 mm to only 500 mm in the total period. Results for Division 4 are similar but less drastic.

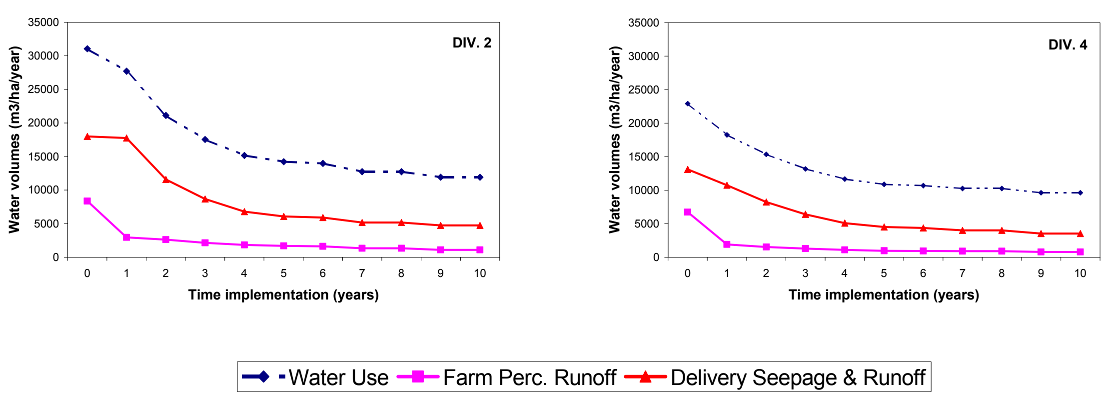


Fig. 11. Foreseen time evolution of the total water use, seepage and branch canals runoff, and farm percolation and runoff for Division 2 and 4.

CONCLUSIONS

The field and modelling studies described in this paper show that water saving and improved water use may be achieved in surface irrigation districts when a combined farm and system approach is adopted. Improvements at farm are constrained by the functioning of the conveyance and distribution systems while upgrading these systems requires changes in farm irrigation scheduling and water application technologies. In addition, particularly for areas where hydrogeological conditions favours the built-up of high water-tables and high evaporation induces salinisation of the soils, water saving and improved water use needs that drainage systems be also improved together with irrigation.

At farm level, results evidence that improving irrigation scheduling without enhancing drainage conditions and the surface irrigation methods and systems is useless because irrigation depths depend on the performance of the farm irrigation. In other words, improving irrigation scheduling alone leads to approaching better calendars but the gross depths to be applied are determined by the water application conditions. Similarly, much better irrigation performances can not be achieved without improving irrigation scheduling and drainage conditions. Moreover, adequate leaching cannot be applied without carefully improvement of the farm systems, precision levelling and larger inflow rates in the case study described herein. Relative to the conveyance and distribution systems, main improvements concern a controlled allocation of water to the branch and sub-branch canals, which implies upgrading both the regulation structures, mainly the cross regulators, and respective management, as well as improving delivery operation rules.

The use of simulation and decision tools that combine field and modelling information confirm its usefulness in this application. Results show that economic benefits corresponding to solutions that are technologically and financially more demanding are limited. Utility values increase from one scenario to the next but such increase is more evident for the scenarios up to scenario 4, which concern strong water saving, controlled drainage and improved farming conditions without heavy technological requirements. Results also show that, despite land and water productivity increase, so augmenting farm returns, the latter are relatively small because the structure of production costs and benefits in peasants' societies do not favour strong economic returns from technological investments.

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