Water Saving in the Yellow River Basin, China.
2. Assessing the Potential for Improving Basin Irrigation

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ABSTRACT

A study focusing the improvement of the basin irrigation is performed in the Huinong Irrigation District (HID), in the upper reaches of the Yellow River basin, Ningxia Province, and in the Bojili Irrigation District (BID), in the lower reaches of the basin, Shandong Province. Studies include the field evaluation of current basin irrigation practices and the use of the simulation models SRFR and SIRMOD to search for improved designs and practices. The target application depths are generated by the irrigation scheduling simulation model ISAREG. For HID, achieving a control of present excess irrigation water applied and the induced water table rise and salinity requires that the basin water advance would be completed in a much shorter time than at present. Therefore, improvements in field sizes, land leveling, infiltration conditions and inflow rates are identified aiming at water savings and controlling waterlogging and salinity. At BID, the main problems relate to excessive field lengths and relatively poor land leveling, which induce very slow advance times, which are associated with excess water application or under-irrigation of the downstream part of the field. Solutions therefore include improved land leveling, larger inflow discharges and reduction of field lengths. The paper summarizes the approaches used to calibrate the simulation models from field observations, an analysis of present conditions and performances, and a discussion on the proposed issues for both areas.

Keywords. Field evaluation, infiltration, irrigation performance, land leveling, simulation modeling, percolation, salinity control.

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1. INTRODUCTION

The Yellow River (YR) is the second largest river in China and the main source of the water uses in the Northwest and North China (Fig. 1). Its basin has a dense population, well-developed agriculture, abundant mineral deposits and a fast growing industrial development, but usually faces drought and water shortages (Cai *et al.*, 2003). Sustainable agricultural development in the basin is possible when considerable water savings in irrigation are attempted, which requires innovative research to improve upon water use in the large irrigation districts.

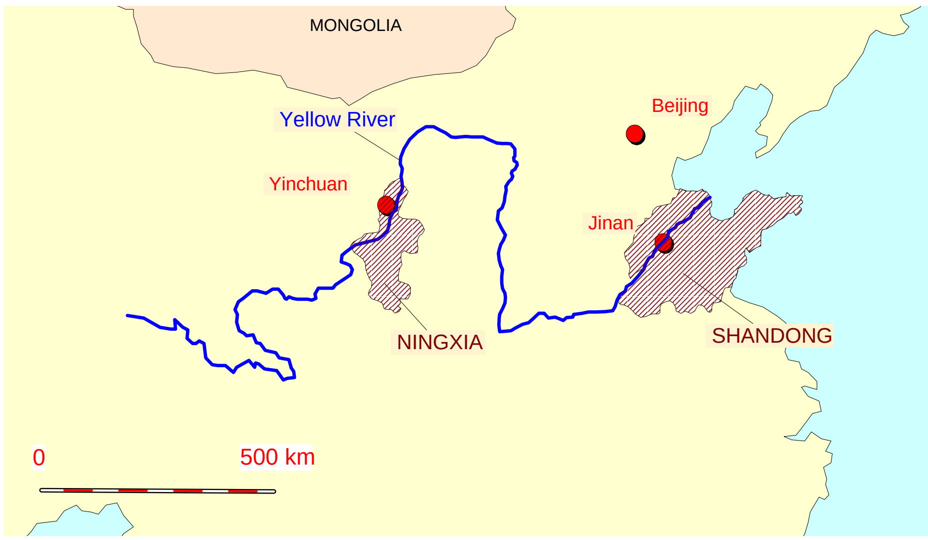


Figure 1. The Yellow River basin with identification of the Provinces where research was developed.

With the objective of supporting further development of water conservation and saving policies, a cooperative research project has been developed from 1998 to 2002 (Pereira *et al.*, 2003b), which aims at supporting further implementation of irrigation water saving policies by the Chinese Authorities and Institutions responsible for irrigation water management The project was applied to only two case-study irrigation districts, one in the upper basin, the Huinong Irrigation District (HID), Ningxia, the other in the low plain region, near the river delta, the Bojili Irrigation District (BID), Shandong (Fig.1). Problems are different in both case study areas because climate, cropping systems, water availability, irrigation systems, waterlogging and salinity, as well as social and water management systems are also different (Cai *et al.*, 2003). Developing the studies both in HID and BID provides for a large range of agricultural, water resources, irrigation, environmental and social conditions, which allow considering differences in research issues and decision support tools among upstream and downstream regions and provide for a wider applicability of research results.

The HID has 74 400 ha irrigated area and is part of the Qingtongxia Irrigation District, which covers more than 330 000 ha. It develops through 5 counties along the Yellow River. Climate in the HID is arid, with an average 190 mm rainfall during summer, and 5 months of dry and cold winter. Cropping systems are basically irrigated wheat x maize intercropped and paddy rice for the spring-summer season. The upland crops are often in rotation with rice and basin irrigation is used. Water diversion is regulated by the Qingtongxia dam and is available for the entire crop season. However, excessive water diversion, poor regulation and control in the conveyance and distribution canals, and inappropriate water management cause serious problems of waterlogging and salinity. The intake volumes are extremely large, corresponding to an average 6 000 mm, thus much above crop irrigation requirements. That excessive diversion of water is due to poor regulation and control in the conveyance canal, which requires that high water levels be maintained to make possible the functioning of the gates that supply the branch canals. Water in excess flows to the drainage channels and ditches or seeps to the groundwater. This causes the malfunctioning of the drainage system, waterlogging and salinity. Soils are silty alluviums originated by sediments transported by the YR from the loess areas. They are naturally non-saline but induced salinity is observed in large areas where water management is poor.

The BID supplies water to three counties for about 110,000 ha total irrigated area. The average rainfall in the BID is 540 mm, mainly during the summer monsoon, from end June to early September. Main crops are the irrigated winter wheat, cotton, horticultural and tree crops, and rainfed summer crops such as maize and soybeans. The annual diverted volumes range from 1005 to 2968 million m^3, thus having a high variation from a year to the next which relates to the inter-annual runoff variability of the YR and to the management decisions to allocate water to the different users in the middle and downstream reaches of the YR. Water is often scarce for irrigation, thus water reuse is common. Farmers use the drainage system, ponds and every depression to store the canal water delivered in excess, runoff water due to rainfall in the monsoon season as well as pumping from the groundwater to satisfy the crop requirements when canal water is not available. As for HID, soils are silty alluviums deposited by the YR through centuries. Further descriptions of HID and BID are provided in the companion paper by Campos *et al.* (2003c) and by Pereira *et al.* (2003b).

Basin irrigation is used in the HID and BID. Basins in HID are generally wide and short and are used for both paddy and upland crops irrigation. However, fields are not zero leveled and land grading is poor. Surface drainage is generally available. Basin dikes are small and paddies are often over-flooded resulting in tail-end runoff. Inflow rates available are not large enough resulting in high advance time. Because farmers cut-off irrigation when advance is completed, irrigation depths applied generally by far exceed the required application depths of upland crops In BID the basins are narrow and long or very long, have a small gradient, and land grading is also poor. The latter systems could be described as sloping border strips with blocked end. Surface drainage is generally also available. As for HID, advance and cut-off times are also too large causing excess water application. The adoption of water saving practices in both cases requires that systems be improved to achieve high irrigation performances.

Modern basin irrigation is widely analyzed in literature. Most papers refer to design issues (e.g. Gonçalves *et al.* 1998; Clemmens, 1998; Strelkoff *et al.*, 2000; Clyma and

Reddy, 2000) and few to research oriented to improve field practices (Clyma and Clemmens, 2000). Clemmens (2000) recently reviewed the positive impacts of level basin improvements on water saving and water productivity, However very few studies relate to applications out of USA, where level basin irrigation was developed. In a study on basin irrigation in the North China Plain (Li and Calejo, 1998), level basin irrigation was proposed as one main approach to implement water saving and increase water productivity. This study also demonstrated that those benefits could only be achieved when improvements in surface irrigation and irrigation scheduling would be implemented together, preferably if soil management was also improved (Pereira *et al*., 2003a). Nevertheless, yield impacts of irrigation depend upon the agronomic practices adopted. Zairi *et al*. (1998) demonstrated the difficulties in improving the performance of border irrigation systems having slopes similar to those of the basins evaluated in China when water is scarce. However, their results are relative to cracking soils, which have a peculiar behaviour. A study developed by the same time in Egypt (Clemmens *et al*., 1999) demonstrated the potential for modern basin irrigation, particularly for long basins, and also evidenced that irrigation performances are affected by cultural practices (El-Haddad *et al*., 2001). In a study applied to North East Syria, the need to improve irrigation systems for better performances was questioned and the hypothesis for just improving the reuse of drainage water due to excess water use in irrigation was considered (Salman *et al*., 1999).

The improvement of the farm irrigation systems is only a part of the modernization required in the YR basin to improve irrigation performances and the effective application of water conservation and saving, as well as to improve water productivity and increase farmers' incomes. Thus, studies were developed in combination with those relative to irrigation scheduling, presented in a companion paper (Campos *et al*., 2003c), Results of both farm irrigation studies were extensively used in an irrigation demand and delivery decision support system (DSS) where scenarios for the farm and distribution systems are evaluated using multicriteria analysis (Gonçalves *et al*., 2002, 2003). These scenario evaluations have shown that improvements in irrigation systems are expected to positively influence the incomes of farmers.

The research reported herein was conducted in parallel with other studies (Pereira *et al*., 2003b), including those relative to paddy rice irrigation (Dong at al., 2000, Mao *et al*., 2003), drainage and salinity control in HID (Hollanders *et al*., 2001, 2003), surface drainage and water-table management in BID (Bouarfa *et al*., 2001, 2003), water reuse in BID (Minhas *et al*., 2001, 2003) and the improvement of the supply systems and management (Roost, 2003; Roost *et al*., 2003). Hypothesis made about drainage improvements in HID are therefore based on assumptions developed through those complementary research findings.

One main objective of this paper is to contribute for a better understanding of surface irrigation systems in North China and issues for their improvement aiming at water saving and conservation. This understanding is of great importance because water saving irrigation in China (e.g. papers edited by Huang, 2000) is generally approached through irrigation scheduling and the adoption of pressurized systems without caring for the potential of modern surface irrigation. Other objectives of this paper are to present the methodology used to assess the irrigation performance in both case-study areas of the YR basin and the approaches used to develop alternative solutions for basin irrigation improvement. This paper describes the actual basin infiltration systems and the respective performances, which are very low at present, the procedures for searching for improved solutions, and benefits expected when improved farm irrigation management would be adopted. The results presented herein refer to few examples because the study interested very large irrigation districts and research could only be more detailed in few locations.

2. BASIN CHARACTERISTICS AND INFILTRATION PARAMETERS

2.1. General

The assessment of the potential for basin irrigation improvement requires that appropriate field data be collected to characterize the farm systems and their performance, as well as to parameterize the models to be used for simulation of alternative improvements. Field evaluations of irrigation events in farmer fields were therefore realized. The methodology for these evaluations is well proved (e.g. Walker and Skogerboe, 1987) including in a former project developed in North China (Li and Calejo, 1998, Li *et al*., 1999). When field data are available, simulation models can be used to estimate the hydraulic roughness and infiltration parameters, and then to design the improved systems.

The surface irrigation simulation model SRFR (Strelkoff, 1993) was used iteratively to optimize the infiltration and roughness parameters using data from field evaluations of irrigation events in farmers fields in Pingluo (HID) and in Huimin and Wudi (BID). Data from infiltrometer tests was used to produce the first estimates of the infiltration parameters to make easier the initial conditions for model optimization. These initial parameters were used with the SRFR simulation model in the inverse solution of the surface irrigation problem to search the optimal parameters, using advance and recession data (Katopodes *et al*., 1990). Clemmens *et al*. (2001) recently analyzed the accuracy and impacts of this estimation method. The field and optimization methodologies were previously successfully used for North China (Li and Calejo, 1998). After consolidating the base data for simulation, a modified version of the model SADREGA (Gonçalves *et al*., 1998; Gonçalves and Pereira, 1999) was used, which incorporates the surface irrigation simulation model SIRMOD (ISED, 1989). Simulations were performed for a variety of soil infiltration conditions relative to the soils and the crop development at time of irrigation. When model solutions did not converge, the SRFR model was then used.

To establish the improved scenarios for surface irrigation, the same target irrigation depths and soil water content at time of irrigation computed with the irrigation scheduling simulation model ISAREG (see Campos *et al*., 2003c) were used with SIRMOD and SRFR models. An interactive approach was adopted when using those simulation models to make sure that the net depths considered in the irrigation schedules are large enough that the field advance can be completed. The interactive exploration of models was aimed at maximizing the irrigation performance and minimizing the percolation.

2.2. Basin characteristics and inflow rates

Field evaluations were performed in the Pingluo county in HID (Campos *et al*., 2003a) and in the Huimin and Wudi counties in BID (Liu *et al*., 2003). The basin geometry measurements included the basin length, width and micro-topography. The micro-topography is described by the average slope, S_o (m m^{-1}), and by the non-dimensional indicator Δy (m m^{-1}), which describes the relative non-uniformity of the field slopes:

$$\Delta y = \frac{100 \sum_{i=1}^{N} \left| y_i - \hat{y}_i \right|}{N\,L} \tag{1}$$

where y_i is the observed elevation (m); $\hat{y}_i$ is the target elevation (m) when the slope would be uniform; N is the number of observations (i=1,…,N); and L is the length of the field (m). The indicator Δy was adopted following a former study (Li and Calejo, 1998) where it has shown good relationships with the basin performance.

The main results concerning the field geometry are presented in Table 1. In HID, basins are of wide rectangular form. Because rice and upland crops are in rotation, the layout of the basin fields is typical for paddies (Fig.2), with an irrigation ditch located upstream of the fields and a tertiary or quaternary surface drain downstream.

Table 1. Observed basin lengths, widths, slopes S_o and non-uniformity Δy.

	Length (m)	Width (m)	S_o (%)	Δy (%)
HID				
Average	37.9	29.0	0.090	0.039
Maximum	46.5	31.9	0.250	0.077
Minimum	24.7	22.6	0.020	0.018
Standard deviation	7.3	2.9	0.070	0.024
BID				
Maximum	280.0	11.0	0.043	0.128
Minimum	44.0	5.2	0.005	0.005

Basins are narrow and often very long in BID, where the smaller widths correspond to the longer basins. The slopes are generally small, < 0.01% in HID and < 0.05% in BID, but non-uniform. The relative non-uniformity in elevation ranges between 0.02 and 0.08% in HID and from 0.005 to 0.128 in BID, where the larger values are for the short basins. This relates to the fact that small basins have often a reversed slope downstream (Fig.3). Basin conditions in HID are adverse for both upland crops irrigation as analyzed below and to paddy irrigation management as assessed by Dong *et al*., (2000) and Mao *et al*. (2003).

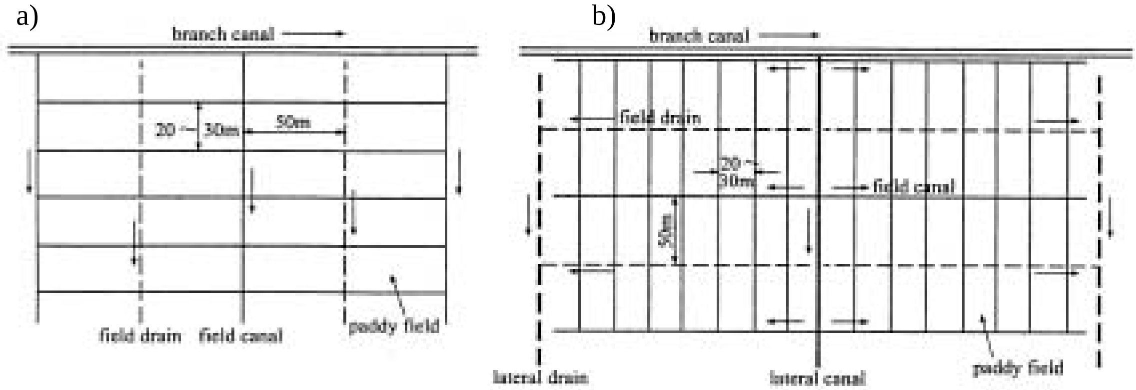


Figure 2. Typical layout patterns of paddy and irrigated fields showing the irrigation and drainage canals and ditches: a) traditional system where the field irrigation canals are supplied from the branch canals, and b) when they are supplied from a sub-branch canal.

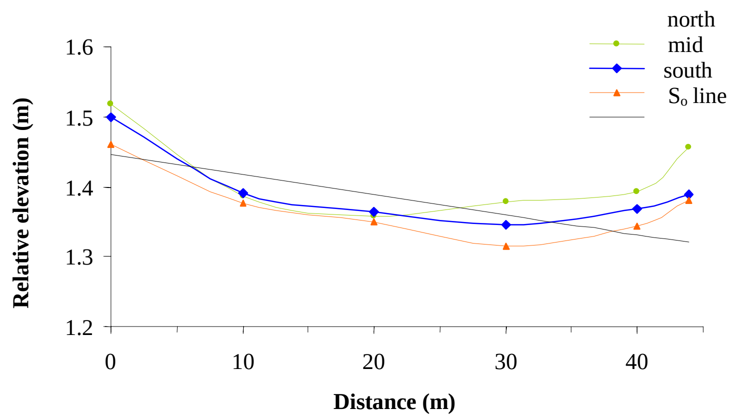


Figure 3. Typical micro-topography conditions of a short basin with reversed slope by downstream, BID.

The inflow rates were measured with small cutthroat flumes (Walker and Skogerboe, 1987). They were selected due to the extremely high sediments charge of the Yellow River water, which produced malfunctioning of long throated flumes and modified broad crest weirs under conditions of low flow velocity. Results in Table 2 show that in HID the inflow discharges by unit width of the basin, Q_{avg} (L s^{-1} m^{-1}), have small variations from the first to the last irrigation. These inflow discharges are small, which is related with the large basin widths (Table 1). Small inflow rates largely contribute to long advance times and, therefore, to excessive supply times and over-irrigation. In BID, the variation of Q_{avg} is much larger, ranging from 1.5 to 4.5 L $s^{-1}m^{-1}$. This variability relates with in the high range of variation of basin lengths and widths (Table 1) and with the water source. Q_{avg} is larger when canal water is used and smaller when water is pumped from drainage canals and the groundwater.

Table 2. Observed inflow rates in HID.

Irrigations	Average ($L\ s^{-1}\ m^{-1}$)	Standard deviation ($L\ s^{-1}\ m^{-1}$)
1st Irrigation	1.2	0.3
2nd Irrigation	1.2	0.5
5th Irrigation	0.9	0.4
6th Irrigation	0.8	0.1

2.3. Hydraulics roughness and infiltration parameters

Field tests using a basin infiltrometer were performed to produce a first estimation of the parameters K and a of the Kostiakov infiltration equation

$$Z = Kt^a \qquad (2)$$

where Z is cumulative infiltration (mm), t is infiltration time (hours), and K ($mm\ h^{-a}$) and a are empirical coefficients. The Kostiakov infiltration is used in the models SRFR and SIRMOD.

Those initial parameters obtained with the basin infiltrometer tests were used to initialize the SRFR simulation model when applying the inverse solution of the surface irrigation problem to search the optimal parameters, using advance and recession data (Katopodes *et al*., 1990; Clemmens, 1991). An iterative approach was adopted, where the Manning's hydraulic roughness parameter n was fixed and the infiltration parameters a and K were varied from one iteration to the next.

The hydraulic roughness coefficients n were selected from field observations and using data from former field studies in similar silty soils, basin irrigation and the wheat crop (Li and Calejo, 1998). For HID, field evaluations included the observation of the flow depth y (m) to derive n as a function of the inflow rate, slope of the water surface and flow depth (Walker and Skogerboe, 1987). Due to the large width of the basins, unevenness of the land surface and small inflow rates, these observations revealed very difficult and only few sets of observed data could be used. However, the values estimated for n were similar to those estimated for the North China Plain, thus the set of n values in Table 3 was obtained from complementing the field estimated values with those from the previous study (Li and Calejo, 1998). For BID, the same approach was applied.

Table 3. The Manning's hydraulics roughness n ($m^{-1/3}\ s$) for the HID basins.

Irrigation order	Wheat	Intercrop	Maize
Winter irrigation	0.12	0.12	0.12
1st irrigation	0.15	0.13	-
2nd irrigation	0.16	0.15	0.14
3rd irrigation	0.16	0.16	0.15
4th irrigation	0.14	0.16	0.18
5th irrigation	-	0.20	0.20
6th irrigation	-	0.20	0.22

Because the similitude of basin and crop conditions was higher there, it was observed that field derived Manning's hydraulics roughness coefficients closely matched those formerly obtained for the North China Plain (Li and Calejo, 1998). The following values were retained: (a) n = 0.1 $m^{1/3}$ s for the irrigation at planting, (b) n = 0.12 $m^{1/3}$ s for the winter irrigation, and (c) n = 0.14 $m^{1/3}$ s for spring irrigations.

In the HID, the water table is high for most of the irrigation season due to the excessive water diversion into the irrigation system (Hollanders *et al*., 2003) as briefly analyzed in the Introduction section. At Pingluo, where field evaluations were performed, the water table depth was only 0.5 m for most of time. Because among the research objectives was the control of the water table to provide for the control of waterlogging and salinity, it was necessary not only to parameterize the infiltration (Eq. 2) for the present conditions but also for those conditions when the water table is lowered to about 1.0 m (Fig. 4). However, there were no locations where the water table was lowered, thus it was not possible to perform observations to parameterize the model for the future scenarios. It has been necessary to perform the parameterization from the actual observation data but assuming different conditions relative to the impact of the water table on the infiltration.

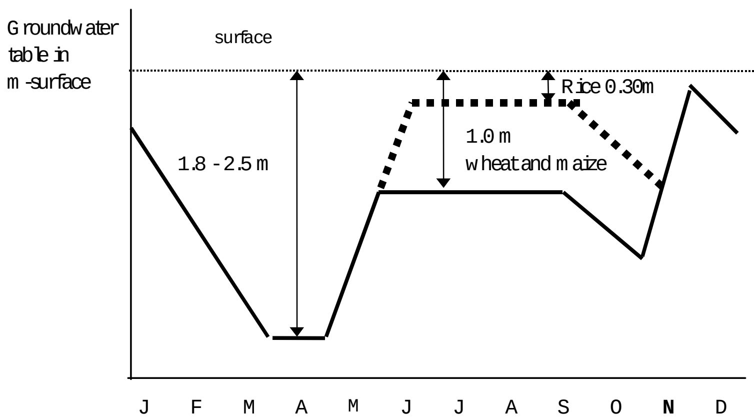


Figure 4. Foreseen water table depth scenario for HID when improved water management be enforced (source: Hollanders *et al*., 2003).

Field observations have shown that recession is much slower than those observed before in the North China Plain and at BID despite soil characteristics are similar. It was then hypothesized that recession is very slow because the groundwater table slows down the water movement through the soil profile. Soil water observations (not shown) confirmed that the soil water content was kept very high after every irrigation events. Therefore, the infiltration parameters obtained for the observed recession could not be used to simulate scenarios where the water table depth is improved. Because the groundwater table less affects the advance, it was also hypothesized that it may change few from the present to future conditions where the water table is lowered. Therefore it was assumed that the infiltration parameters estimated with SRFR by optimizing both the advance and recession represent the present conditions and scenarios relative to a lower water table could be represented by the optimization of the advance only. There are some weaknesses in this assumptions because it is well known that the parameters K and a are not independent and may vary together along the optimization procedure. However, this was the only possibility to formulate an admissible hypothesis for the expected infiltration conditions.

Assuming the hypothesis explained above for HID, the inverse solution of the surface irrigation problem to estimate the infiltration parameters was performed in two steps, as exemplified in Figure 5. First, the search of the parameters was performed using advance data only. In this optimization none of the infiltration parameters were fixed. Then, the optimization procedure was used to search the parameters using advance and recession observed data. In this search, the parameter K obtained from the advance optimization was kept constant and only the optimal value for *a* was searched. Keeping *a* and searching for *K* induced larger variation of the parameters.

From the hypothesis above, the parameters obtained when both the advance and recession were used for the optimization correspond to the present conditions, where infiltration is influenced by the water table. Those parameters optimized using the advance data only are assumed as the best estimates for conditions having a lower water table. As shown in Fig. 5a, the simulated recession is then much faster than that observed for present as it may be expected when the watertable will impact less the water redistribution through the soil profile.

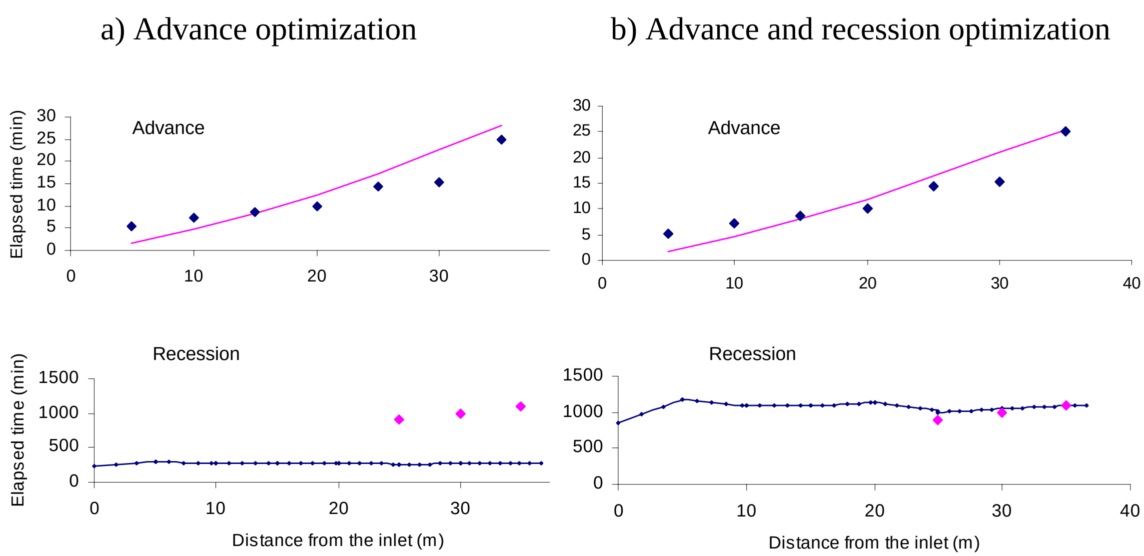


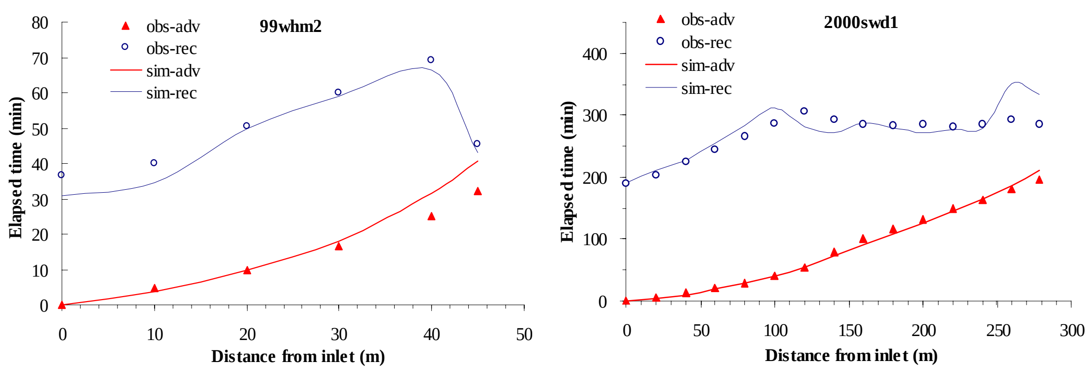
Figure 5. Field B2 (HID), 5th irrigation: results of the simulated vs. observed advance and recession for: (a) advance optimization, and (b) advance and recession optimization.

Based on the field evaluations performed and on the soil hydraulic properties measured in laboratory from samples collected in several locations along the HID area, three types of soil infiltration conditions were considered. The respective estimated Kostiakov infiltration parameters for both water-table scenarios are shown in Table 4.

Table 4. Parameters of the Kostiakov infiltration equation, HID.

Irrigation order		Parameters K and a for the three infiltration soil types					
		Average		Low		High	
		K (mm h^{-a})	a	K (mm h^{-a})	a	K (mm h^{-a})	a
1st	Present	47.5	0.44	30.4	0.33	74.2	0.54
	Target	79.2	0.56	44.7	0.42	140.5	0.70
2nd	Present	34.2	0.47	21.2	0.35	55.5	0.59
	Target	63.3	0.62	33.6	0.46	119.4	0.78
3rd	Present	17.6	0.40	15.4	0.37	42.1	0.61
	Target	55.4	0.68	27.6	0.51	111.0	0.85
4th	Present	23.8	0.49	14.4	0.37	39.4	0.61
	Target	51.8	0.68	25.8	0.51	103.9	0.85
5th & 6th	Present	23.2	0.50	13.9	0.38	38.8	0.62
	Target	50.6	0.69	25.0	0.52	102.7	0.86

For BID, the infiltration parameters for both experimental areas (Huimin and Wudi) and different irrigation timings were estimated using the SRFR model to search for the optimal fitting of the advance and recession curves observed in field evaluations. Examples of fitting for a short basin at Huimin and a long basin at Wudi are presented in Fig. 6. The impact of the reversed slope downstream in the short basins (Fig. 3) is well evident on the reduced opportunity time for infiltration near the downstream end (Fig. 6a). For the long basin (Fig. 6b), the unevenness of the field surface causes a significant decrease of the opportunity time for infiltration in the last two thirds of the field.



(a) Winter irrigation in Huimin

(b) Spring irrigation in Wudi

Figure 6. Observed and simulated advance and recession: (a) winter irrigation in a short basin at Huimin, and b) spring irrigation in a long basin at Wudi.

From the observations performed and parameter estimation as described above, as well as considering the soil hydraulic properties estimated for several locations (Liu *et al.*, 2003) two main type of soil infiltration were considered (Table 5).

Table 5. Parameters of the Kostiakov infiltration equation for soils with low and high infiltration, BID.

Irrigation timings	Parameter K (mm h^{-a})		Parameter a	
	Low infiltration	High infiltration	Low infiltration	High infiltration
At planting	50.00	75.01	0.55	0.60
Winter	69.96	100.00	0.55	0.50
Spring	84.97	110.02	0.50	0.45

3. ACTUAL IRRIGATION PERFORMANCES

The analysis of the actual irrigation performances was done with the SRFR model using field evaluations data and considering the infiltration depth required, Z_{req} (mm), computed with the ISAREG model using daily rainfall and evapotranspiration data (Campos *et al*., 2003a; 2003b). Results shown herein are relative to weather data relative to Pingluo for HID and Huimin for BID. However, in this study data relative to all counties were used. These simulations with SRFR where performed for the actual uneven leveling, not the average slope. Actual irrigation performances for HID refer to the actual water table depths.

The computed values for Z_{req} are shown in Table 6, where they are compared with the observed average depths applied D (mm). In the HID, the irrigations refer to wheat intercropped with maize. The first is generally applied by April, before maize planting, and the last two are given after wheat harvesting. In BID the irrigations refer to winter wheat: the first at planting, the second before soil freezing, early December, and the last by the spring. Often, a second spring irrigation is applied but using drainage water or groundwater.

Table 6. Average application depths observed (D) and required (Z_{req}).

Irrigation number	HID		BID	
	D (mm)	Z_{req} (mm)	D (mm)	Z_{req} (mm)
1st	109	92	100	71
2nd	108	30	135	43
3rd	95	51	150	142
4th	111	17	-	-
5th	92	40	-	-
6th	116	14	-	-

Results for the actual irrigation performances in HID are shown in Table 7, including the distribution uniformity, DU_{lq} (%), and the application efficiency, AE_{lq} (%), relative to the low quarter as defined by Pereira and Trout (1999), and the percolation volumes.

Table 7. Irrigation performances observed in farmers' fields at HID.

Irrigation number	Field	q ($L\ s^{-1}\ m^{-1}$)	D (mm)	Z_{lq} (mm)	AE_{lq} (%)	DU_{lq} (%)	Percolation (mm)
1st	B1	1.4	109	67	62	61	24
	B3	1.0	107	97	86	91	15
2nd	B1	1.3	100	57	30	57	70
	B2	1.0	127	121	23	96	96
	B3-1	0.6	67	64	45	95	37
	B3-2	1.0	56	53	53	94	27
	B3-3	2.2	85	83	35	98	55
	C1	0.9	111	93	27	83	81
	C2	0.7	136	120	22	88	106
	C3	0.9	94	80	32	85	64
	C4	0.8	90	79	34	88	60
3rd	B3-1	0.6	81	76	63	94	30
	B3-2	1.1	77	74	67	97	26
	B3-3	3.2	124	122	41	99	73
	C1	0.9	112	94	46	84	61
	C2	0.4	94	78	54	83	43
	C3	0.6	114	100	45	87	63
5th	B1	1.2	94	50	43	53	54
	B2	1.2	134	128	30	96	94
	C1	1.2	117	99	34	84	77
	C3	0.4	105	90	35	86	65
	C4	0.7	157	145	26	93	12
6th	B2	0.9	97	92	14	94	83
	C2	0.7	141	125	10	88	127

Results show that DU_{lq} are generally high but AE_{lq} are very low. The latter are explained by the large differences between D and Z_{req} depths (Table 6), which reflect the influence of the very high water table, which maintains the soil water at high water contents due to capillary fluxes (Campos *et al.*, 2003a; 2003c). Observed soil water contents (not shown) confirmed these conditions. Since basins are fully diked and runoff does not occur, all excess water percolates to the water table, thus helping to maintain the existing high water table. However, as identified through the groundwater and drainage studies (Hollanders *et al.*, 2003) the main contribution for the presently high water table is the excessive volume of water diverted into the conveyance and distribution system and not the percolation from the farmer fields. Therefore, in building improved scenarios, lowering the water table through improved off-farm water management was considered an essential pre-condition.

Results for BID (Table 8) also show relatively high DU_{lq} and higher AE_{lq} than for HID. Low AE_{lq} and high percolation is observed for the second irrigation, i.e. the winter irrigation, which shows a large difference between D and Z_{req} (Table 6). This results from the fact that farmers always irrigate by the winter time, when water is available, including when the soil water depletion is small, because that irrigation favors soil microporosity due to the successive soil water freezing and melting effects.

Table 8. Winter wheat Irrigation performances evaluated in farmer's fields in Bojili.

Irrigation number	County	Field	L (m)	q (L/s/m)	D (mm)	Z_{lq} (mm)	AE_{lq} (%)	DU_{lq} (%)	Percolation (mm)
Planting	Huimin	B6	44	3.2	35	25	71	70	0
		B8	44	3.0	65	29	45	45	14
	Wudi	B7t	80	4.0	39	36	92	93	0
		B8	80	3.0	56	49	88	88	0
		B3	280	4.0	151	101	67	67	44
Winter	Huimin	B4	44	1.5	66.	55	46	84	36
		B4'	44	1.8	95	62	32	65	65
		B6	44	1.8	65	51	46	78	35
		B8	44	2.0	106	103	28	97	78
	Wudi	B7	80	2.2	78	74	81	95	15
		B3	280	2.7	143	109	44	76	79
		B7'	280	2.7	142	106	44	75	79
Spring	Huimin	B6	44	3.2	97	64	66	66	0
		B8	44	3.0	103	63	61	61	4
	Wudi	B7	80	3.7	143	132	77	92	32
		B8	80	2.9	183	171	60	93	73
		B3	280	4.6	186	164	59	88	75
		B7'	280	4.4	178	160	62	90	67

Larger percolation was observed for the long basins, which is due to the very long supply time required for the advance to be completed. The cases observed with zero percolation and high AE_{lq} correspond to under-irrigation events as shown by the relatively low infiltration in the last quarter, Z_{lq}. To be noted that, differently to HID, percolation is not a problem in BID because it recharges the shallow groundwater, which is used for irrigation during times when canal water is not available (Bouarfa *et al.*, 2003).

4. IMPROVEMENT OF BASIN IRRIGATION SYSTEMS: SIMULATION ANALYSIS

4.1. Huinong Irrigation District

Simulation studies were performed to search for appropriate improvements to the basin irrigation systems considering that the target groundwater table depth can be achieved. Improvements for conditions where the water table remains high are generally not feasible because it is extremely difficult to modify the basins and the basin management to apply the required small irrigation depths as such in Table 6.

A simulation analysis of irrigation performances was first developed considering the actual fields referred in Table 7 without improving land leveling. As for the present conditions, these simulations with SRFR where performed for the actual uneven leveling, not using the average slope. The target application depths Z_{req} were computed with the irrigation scheduling model ISAREG assuming that the groundwater depth would be lowered to 1.0 m. Simulations were performed for the most common soil types, considering leaching requirements of 10% of the irrigation depths (Campos *et al*., 2003a). This improved schedule for the intercrop requires only 5 irrigations instead of the present 6. Table 9 refers to basin B1 only. Several inflow rates were selected, the smaller corresponding to conditions closer to the present ones, and the other to represent progressive improvements. Larger inflow rates lead to shorter advance and application times, T_{ap} (min), thus basin irrigation performances are positively influenced by large inflow rates, mainly when level-basin irrigation is adopted (Clemmens *et al*., 1999).

Table 9. Simulated irrigation performances for the actual field topography (field B1) and average infiltration, when the irrigation scheduling would be improved (intercrop, HID).

Irrigations after planting	Z_{req} (mm)	q (L s-1 m-1)	Tap (min)	D (mm)	AE_{lq} (%)	DU_{lq} (%)	Percolation (mm)
1st	110	1.4	100	168	65	77	58
		2.0	71	171	64	76	61
		3.0	48	173	64	76	63
2nd	110	1.3	110	171	65	76	61
		2.0	72	172	64	76	62
		3.0	48	173	64	75	63
3rd	110	1.0	142	170	65	77	60
		2.0	72	173	64	76	63
		3.0	49	175	63	75	65
4th	110	1.0	143	171	64	77	61
		2.0	73	174	64	76	64
		3.0	49	175	63	75	65
5th	110	1.2	119	171	64	76	61
		2.0	73	174	63	76	64
		3.0	48	174	63	75	64

Results in Table 9 show that the achievable distribution uniformity DU_{lq} and application efficiency AE_{lq} are higher those observed (Table 7). However, DU_{lq} and AE_{lq} are below the potential values and the percolation is still excessive. Therefore, the scenario for improving the irrigation scheduling but not the land leveling do not show enough appropriate for both water savings and maintaining the water table at the target level as required for water-logging and salinity control.

To better understand the differences between the present and the predicted conditions, results for the second irrigation in the same basin B1 are shown in Fig. 7: at present, due to the very high water table impacts, Z_{req} is very small, causing that a very large fraction of the applied depth percolates to the water table (Fig,7a). When the latter would be lowered to 1.0 m depth, Z_{req} is much higher but percolation still occurs due to the uneven slope of the field (Fig 7b). Increasing the inflow rates q does not provide for any significant improvement of the application efficiency AE_{lq} or the distribution uniformity DU_{lq} even though the application time T_{ap} is reduced (Table 9). This is due to the fact that, because basin slopes are relatively high, increasing the inflow rate produces higher infiltration in the last quarter of the field (Fig. 7b). This is true for basins with slopes higher than that of field B1 (S_o = 0.025 %) but not for fields with zero slopes.

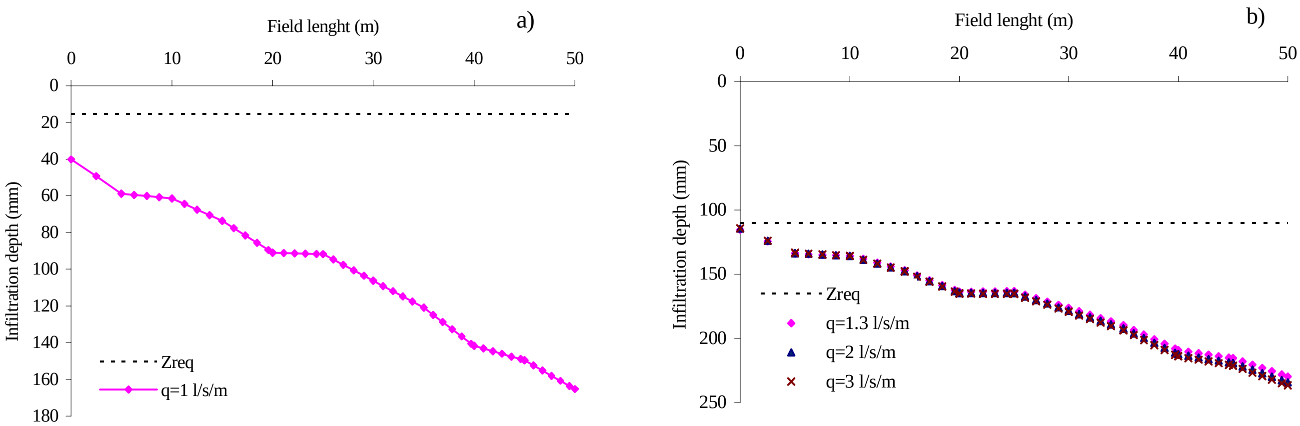


Figure 7. Infiltrated depth curves for the second irrigation in basin B1: (a) at present and (b) when adopting an improved scheduling and the target water table depth, comparing several inflow rates q (L s^{-1} m^{-1})

As analyzed above, despite the fact that irrigation efficiencies increase when irrigation timings and depths are appropriate, infiltration is not uniform enough along the basin. Therefore, precision leveling is considered for implementing zero slope basins, currently named precision level basins. The importance of precision leveling was evidenced in the former research study (Li and Calejo, 1998; Pereira *et al.*, 2003a) and is well discussed by several authors (e.g. Playan *et al*., 1996; Fangmeier *et al*., 1999; Zapata and Playan, 2000).

Simulations to assess the potential for precision level basin irrigation were performed for the same infiltration conditions as in Table 9 with Z_{req} = D, computed to minimize percolation under the assumption that salt leaching is mainly performed during the winter irrigation. Results in Table 10 show very high distribution uniformity (DU_{lq}) and application efficiency (AE_{lq}), as well as very low percolation when the inflow rate q is close or larger than 1 L s^{-1} m^{-1}. Positive impacts on yields may be expected because the depths infiltrated in the lower quarter of the fields, Z_{lq} (mm), are close to the target Z_{req}. These results are significantly better than those in Table 9 and indicate that precision level basin irrigation may be an adequate technology to be implemented in HID. In addition, when upland crops are in rotation with rice, there is advantage to adopt zero slope leveling for the paddies, mainly when small water depths are intended to be maintained in the paddies as for the proposed adoption of a water saving irrigation method (Mao *et al*., 2003). Drawbacks for level basins relative to possible causing of water-logging following rain storms may be avoided because surface drainage exists (Fig. 2) and the low frequency of rainfall in the area suggests instead to raise the basin dikes for better capturing rainfall (Mao *et al*., 2003).

Table 10. Simulated level basin irrigation performances for the intercrop considering the target water table depth and precision leveling for a field length of 48m in HID.

Irrigation number	Z_{req} (mm)	q ($L\ s^{-1}\ m^{-1}$)	D (mm)	Z_{lq} (mm)	AE_{lq} (%)	DU_{lq} (%)	Percolation (mm)
1st	110	1	130	112	85	86	20
		2	118	110	93	93	8
		3	113	107	95	95	3
2nd	110	1	123	110	90	90	13
		2	115	109	95	95	5
		3	113	108	96	96	3
3rd	110	1	119	108	91	91	9
		2	115	110	95	95	5
		3	111	107	96	96	2
4th	110	1	119	110	92	92	9
		2	114	109	96	96	4
		3	113	109	97	97	3
5th	110	1	120	111	91	92	10
		2	112	108	96	96	3
		3	112	109	97	97	3

Higher inflow rates play a main role in improving the distribution uniformity DU_{lq} and the application efficiency AE_{lq}, as well as for controlling the percolation. This is due to the fact that higher inflow rates produce smaller advance times (Fig 8 b) which lead to more uniform infiltration, mainly due to decreased infiltrated depths in the lower quarter of the field, Z_{lq}, as shown by comparing Fig. 9 with Fig. 7, the latter relative to a sloping basin. Therefore, when higher inflow rates are applied, the percolation depths become smaller and the infiltration is more uniform along the field. These conditions are also more favorable for controlling the leaching fraction in case of saline soils, which are common in HID. Results for other fields, not shown herein, are similar to those for basin B1 taken as example.

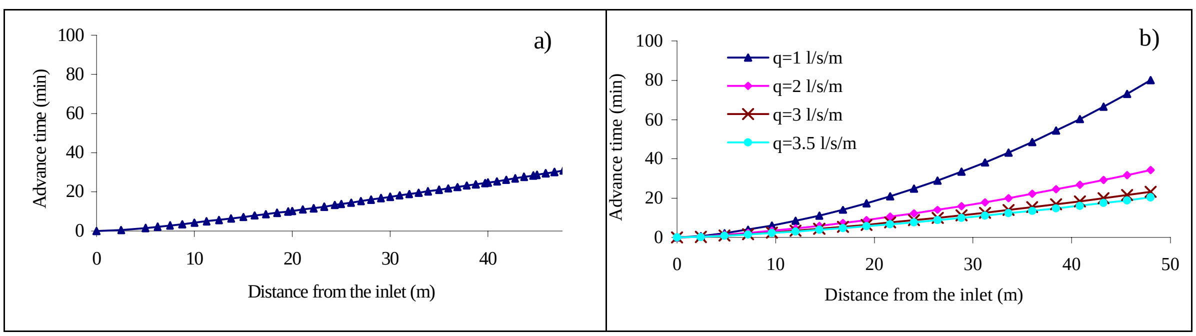


Figure 8. Advance curves for field B1: (a) actual conditions, with average slope 0.025%; and (b) simulated for a precision zero leveled basin with inflow rates ranging from 1 to 3.5 $L\ s^{-1}\ m^{-1}$.

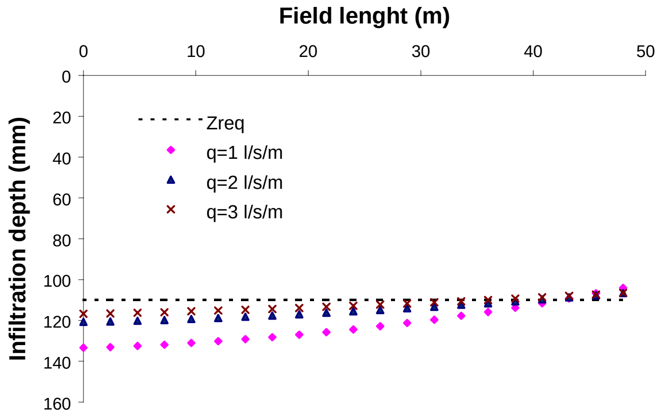


Figure 9. Infiltration depth curves simulated for field B1 adopting precision zero leveling and inflow rates ranging from 1 to 3 l/s/m (see Fig. 3b).

As analyzed above, precision zero leveled basins, or precision leveling irrigation, are the most appropriate for HID to achieve high irrigation performances, controlling percolation into the groundwater, application of the appropriate leaching fractions, and therefore controlling the salinity and the water table at its target level.

4.2. Bojili Irrigation District

As identified earlier when discussing the actual irrigation performances, problems in BID are different from those in HID, thus requiring different approaches.

A simulation analysis was first performed for typical field lengths, 44 m and 150 m, and the more common slopes and inflow rates. Simulations for 280 m length were also performed but significant improvements were never attained. It was considered that such long basins should better be subdivided into two with 140 m each, which behavior is similar to that of basins 150 m long. Z_{req} was computed with the ISAREG model for winter wheat, as described in the companion paper (Campos *et al*., 2003c).

Results for the typical short basins (44 m) with relatively high slope (0.3 %) are shown in Table 11. Sloping basins (or blocked border strips) were considered following the wishes of BID staff aiming at avoiding waterlogging when heavy monsoon rains occur. They do not show any improvement relatively to present conditions (Table 8) but on the contrary, the percolation would be higher. These basins behave similarly to those in Fig. 7: adopting higher inflow rates, infiltration and percolation tend to increase downstream and uniformity is not improved.

For these short basins, since the percolation increases toward the downstream end when the irrigation is intended to be completed, the best approach is to reduce the field slope or to adopt level basin irrigation. Only the case for 0.1% slope precisely leveled is presented here because it corresponds to the wishes of the local staff. Results for precision level basins are similar to those analyzed before for HID (Table 10) and were considered in the set of scenarios analyzed with the DSS model (Gonçalves *et al*., 2003).

Table 11. Irrigation performance for a field with a length of 44m and slope 0.3% precisely leveled in BID.

Irrigation	Z_{req} (mm)	q (l s-1m-1)	T_{ap} (min)	D (mm)	AE_{lq} (%)	DU_{lq} (%)	Z_{lq} (mm)	Percolation (mm)
Winter	100	2.5	47	160	62	69	112	60
		3.5	32	162	62	70	114	62
Spring	130	2.5	56	191	68	75	144	61
		3.5	40	191	68	75	143	61

Results in Table 12 show that both AE_{lq} and DU_{lq} are largely higher than for present (Table 8) or for the case when slopes would be kept relatively high (Table 11). Percolation is also reduced and the infiltrated depth in the lower quarter of the field (Z_{lq}) is only slightly larger than the target Z_{req}. Thus, adopting 0.1% slope precisely leveled may be an appropriate solution for these fields where surface drainage is poor. Slightly higher performances and less percolation could be achieved with zero slope but differences are not significant enough relative to the 0.1% slope fields.

Table 12. Irrigation performances for a field with a length of 44m and 0.1% slope precisely leveled in BID.

Irrigation	Z_{req} (mm)	q ($l\ s^{-1}m^{-1}$)	T_{ap} (min)	D (mm)	AE_{lq} (%)	DU_{lq} (%)	Z_{lq} (mm)	Percolation (mm)
Winter	100	1.5	58	119	84	88	104	19
		2.5	35	119	84	87	104	19
		3.5	25	119	84	87	104	19
Spring	130	1.5	70	143	91	91	131	13
		2.5	43	147	89	90	133	17
		3.5	31	148	88	90	134	18

In the case of long basins (Table 13), which generally have smaller slopes than the short basins, results from adopting an improved irrigation scheduling but maintaining the same average slope show relatively low uniformity and efficiency, similar to those observed at present and worst than for the sloping short basins in Table 11. Moreover, percolation is too high. Due to the slope, the infiltrated depths in the lower quarter of the field (Z_{lq}) are higher than Z_{req}, particularly for the winter irrigation , thus indicating that infiltrated depths upstream are lesser. Changes in basin slopes were thus analyzed as shown in Table 14.

Table 13. Irrigation performance for a field with a length of 150m and 0.15% slope precisely leveled in BID.

Irrigation	Z_{req} (mm)	q ($l\ s^{-1}m^{-1}$)	T_{ap} (min)	D (mm)	AE_{lq} (%)	DU_{lq} (%)	Z_{lq} (mm)	Percolation (mm)
Winter	100	2.5	190	190	53	60	114	90
		3.5	141	197	51	59	118	97
Spring	130	2.5	160	160	81	81	131	30
		3.5	145	203	64	65	133	73

Results in Table 14 relative to long basins compare precise leveling with zero slope and 0.05 % slope and show that the zero slope is expected to be the best solution. For all cases, DU_{lq} and AE_{lq} are improved and the percolation is smaller than for current conditions (Table 8) or when the 0.15 % slope is considered (Table 13). Winter irrigations show significantly better performances for zero leveling while the spring irrigations show similar results for both slopes. The best results for zero leveling are obtained with higher inflow rates, which is explained by the shorter advance and application times in agreement with conclusions by Clemmens *et al.* (1999). Contrarily, for the 0.05 % slope the best performances are for q = 2.5 L $s^{-1}m^{-1}$. Due to the slope, higher is the inflow rate larger is the fraction infiltrated in the downstream part of the field. However, Z_{lq} are close to Z_{req} in both cases. Therefore, no definitive conclusions may be taken from this analysis except that precision leveling is required and that slopes should be zero or not exceed 0.05 %.

Table 14. Irrigation performances simulated for a field with a length of 150 m in BID adopting various precision level slopes (%) and inflow rates q (L $s^{-1}m^{-1}$).

Irrigation	Z_{req} (mm)	Slope (%)	q (L $s^{-1}m^{-1}$)	T_{ap} (min)	D (mm)	AE_{lq} (%)	DU_{lq} (%)	Z_{lq} (mm)	Percolation (mm)
Winter	100	0.05	2.5	122	122	82	84	103	23
			3.5	91	127	78	83	106	27
			4.5	70	126	79	82	103	30
		0	2.5	115	115	87	90	104	15
			3.5	78	109	92	92	100	9
			4.5	60	108	93	93	101	8
Spring	130	0.05	2.5	130	130	98	99	128	1
			3.5	105	147	88	90	133	17
			4.5	84	151	83	88	134	21
		0	2.5	158	158	82	85	136	28
			3.5	106	148	87	89	133	19
			4.5	80	144	88	91	135	17

Results of this study are in agreement with those from a former project (Li and Calejo, 1998; Pereira *et al*., 2003a) where improvements were tested in farmers' fields and led to increased yields and revenues.

5. CONCLUSIONS

Several conclusions may be drawn from this study. First, the field evaluations performed were essential to characterize the basin irrigation systems and to parameterize the surface irrigation simulation models. The models, after appropriate parameterization, were useful to identify improvements in the system and to predict the respective performances.

The present irrigation conditions in the HID show very low performances, mainly low irrigation efficiency and high deep percolation. However, these depend less on farm management than on the impacts of the high water table. Lowering the water table is a pre-condition to improve farm irrigation. To maintain the water table at a lower level requires that the irrigation systems be improved. Adopting appropriate irrigation timings and depths contributes to improve irrigation performance but the distribution uniformity remains low, which hampers the control of percolation and leaching. Predictions relative to implementing precision zero leveling indicate that irrigation performances can be significantly improved favoring large water savings, the control of the leaching fractions and the control of percolation.

In the BID, problems are less than at HID but irrigation performances are generally low. Large variations in basin length and width make the selection of more appropriate improvements relatively complex. With existing slopes, adopting a better irrigation schedule could produce better performance for the short basins but not for the long ones, where percolation is still excessive. Therefore, it is advisable to adopt precise leveled basins with a 0 to 0.1 % slope when these are short (40 m), and a zero or a mild slope (0.05%) when they are long (150 m). The very long basins, having 280 m length, should be divided into two, with 140 m each, which behave like those 150 m long. In general, improving the irrigation systems would allow adoption of an improved irrigation schedule, minimizing percolation and controlling the leaching fraction when it is required, as well as . increased yields.

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