

Evaluation on the potential of improving border irrigation performance through border dimensions optimization: a case study on the irrigation districts along the lower Yellow River

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Abstract In the Yucheng region along the lower reach of the Yellow River, current border irrigation systems in all three irrigation districts have low irrigation performances with the applied depth per irrigation event >150 mm, and application efficiency <65 %. It is often difficult to change irrigation practices, and rates of adoption are usually slow for China's small-scale farmers. This study emphasizes the feasibility of optimizing border dimensions in border irrigation taking into consideration the existing irrigation conditions and farmers' methods of irrigation practice. The performances of current border irrigation systems and improved systems were evaluated using agricultural irrigation survey data, field experimental data, and a simulation model. The irrigation conditions, that is, inflow rate, border dimensions, and relative cutoff distance, in the irrigation districts were found to be diverse. However, after border dimensions were optimized through simulation and field

testing, it was determined that the applied depth per irrigation event could be decreased by an average of 49 mm, and the application efficiency could be increased on average by 26.7 % in the three irrigation districts. The annual potential amount of water savings among the three districts was calculated to be approximately $5,551 \times 10^4$ m³ in the Yucheng region. Optimizing border dimensions is a practical technology for small-scale farming practices in the irrigation districts along the lower Yellow River.

List of symbols

σ_L	The standard deviation of border lengths
σ_W	The standard deviation of border widths
τ	The intake opportunity time
a	Empirical fitting parameter describing the transient infiltration behavior
a_{ave}	Averaged infiltration parameter a
A	The cross-sectional flow area per unit width
AE	Application efficiency of irrigation
b	Basic soil intake rate
c	A storage term describing the instantaneous infiltration through macropores (in this study, $c = 0$)
CV_L	The coefficient of variation of border lengths
CV_W	The coefficient of variation of border widths
D_{app}	The average depth applied to the field
D_{min}	The minimum infiltrated depth along field length
D_r	The average depth added to the root zone storage
DU_{min}	Distribution uniformity of irrigation
k	Empirical fitting parameter describing the transient infiltration behavior
k_{ave}	Averaged infiltration parameter k
L	Border length
L_{max}	The maximum of border lengths
L_{mean}	The mean of border lengths

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$L_{\text{med.}}$	The median of border lengths
L_{min}	The minimum of border lengths
$L_{\text{opt.}}$	The optimized border length. In this study, $L_{\text{opt.}}$ is defined as the lengths with border irrigation performances of AE greater than 80.0 %, D_{app} less than 125.0 mm, and DU_{min} greater than 80.0 % under practical management
n	Field roughness coefficient
n_{ave}	Averaged field roughness coefficient
Q	Inflow discharge per unit width of the border
Q_0	Inflow rate in irrigation
$Q_{0\text{mean}}$	Mean inflow rate
R	Relative cutoff distance, ratio of advance at cutoff to field length
S_f	The friction slope obtained from the Manning formula
S_0	The slope of borders
t	The time elapsed since the start of irrigation
T	Cutoff time
T_{mean}	Mean water supply time for unit area (0.067 ha) per irrigation event
W	Border width
W_{max}	The maximum of border widths
W_{mean}	The mean of border widths
$W_{\text{med.}}$	The median of border widths
W_{min}	The minimum of border widths
$W_{\text{opt.}}$	The optimized border width, it is defined as the widths with irrigation requirements met and convenience for field practice, and inflow rates within the different irrigation districts are also considered
x	The distance the water flow front has advanced along the border
y	The flow depth
z	The infiltrated depth

Introduction

The irrigation districts along the lower reach of the Yellow River are very important bases for grain production, with abundant tilled land and rich photo-thermal resources, as well as irrigation water from the Yellow River. In this region, 73.7 % of surface water and 70.3 % of groundwater are used for farmland (MWR-YRCC 2009). In the last decade, annual water amounts available for agriculture have continuously decreased (MWR-YRCC 2008), so water savings is critical for agricultural practice (Xu and Gao 2008). However, in this area high amounts of irrigation are being applied (Jia 1999; Gong et al. 2000). Li (2003) reported that the mean annual water application amount in the irrigation districts along the lower Yellow

River was up to 481 mm, which exceeds the irrigation water requirement of 400 mm (Liu et al. 2009).

Excessive irrigation wastes water and further produces nutrient, pesticide and herbicide leaching, groundwater pollution, and secondary soil salinization and alkalization (Asare et al. 2000, 2001; Fang and Chen 2001; Zhu et al. 2005; Feng et al. 2005; Hollanders et al. 2005; Fang et al. 2006; Wang et al. 2004, 2010). Therefore, applied irrigation depth should be reduced according to crop water demands to save water and reduce the potential environmental risks (Fang and Chen 2001; Wang et al. 2004; Pereira et al. 2007).

Compared to other surface irrigation methods, border irrigation dominates in the irrigation districts along the Yellow River. For border irrigation systems, system variables (i.e., inflow rates, border dimensions, slopes, microtopography, and soil infiltration properties) and farmers' management methods substantially affect irrigation performance (Pereira 1999; Pereira et al. 2002). Raine et al. (1997) and Smith et al. (2005) suggested that irrigation application efficiency could be improved to a great extent using a suitable rate of water application and appropriate supply time for specific soil conditions. Moreover, field topography (i.e., the field slope, basin microtopography and its spatial variability, and precision in land grading) also affects the performance of border irrigation systems due to its influence on the advance and recession processes (Walker and Skogerboe 1987; Li and Calejo 1998; Fangmeier et al. 1999; Clemmens et al. 1999; Li et al. 2001a, b; Bai et al. 2007, 2008, 2010). As for the irrigation districts along the Yellow River, improvements in basin inflow discharges, land leveling, and irrigation scheduling could result in a water-savings rate of 33 % (Pereira et al. 2007). All of these improvements require additional investments into field surface amendments and strong irrigation management skills for controlling the field inlet discharge and the water supply time; however, these technologies seem difficult for Chinese farmers to adopt.

In China, farmers play a major role in managing irrigation systems (Pereira et al. 2002). Agricultural practice is primarily performed on small farms (with an average area of 0.105 ha per field plot in our survey; Rozelle and Swinnen 2004), and the ability of farmers to apply modern irrigation technologies is limited. In practice, farmers empirically adopt water-saving technologies based on local irrigation history and their own farm budgets. Among all water-saving technologies, only household-based technologies have been widely adopted due to low cost and minimal requirements of coordination and skills (Blanke et al. 2007; Khan et al. 2009). Currently, the most popular irrigation pattern adopted by farmers in northern China is that farmers cut off irrigation when advance is completed, and thus irrigation-applied depths commonly exceed required

depths (Pereira 1999; Pereira et al. 2002). In the irrigation districts along the Yellow River, border irrigation is adopted by farmers because the method requires few management skills and minimal capital investment, for example, fuel charges or electricity fees for pumping. This means that any adoptive alternatives to improve border irrigation performance should be economical and flexible for farmers.

Currently, factors such as the rate of discharge of the water supply and the relative cutoff distance seriously affect border irrigation performance. Generally, adjusting border dimensions is an easy low-cost technology, and thus the technology of border dimensions optimization is suggested for farmers in the irrigation districts along the lower reach of the Yellow River to effectively improve irrigation performance. Border dimensions have been adjusted to improve irrigation performance in the irrigation districts of the upper-middle Yellow River (Liu and Cai 2002; Li and Rao 2003; Liu et al. 2005; Shi and Ma 2005). However, there is a lack of specific data pertinent to the study area.

The objectives of this study were to (1) evaluate the performance and management practices of current border irrigation systems, (2) optimize border dimensions and evaluate the performance of improved border irrigation systems, and (3) evaluate the water savings in border

irrigation due to the optimization of border dimensions in the Yucheng region.

Materials and data

Study area

Our study area, Yucheng, is located in the Panzhuang irrigation district along the lower Yellow River (Fig. 1). Fluvo-aquic and light salinity fluvo-aquic soils dominate the region. Groundwater depth is variable in time and space due to seasonal changes and different irrigation practices. For example, the groundwater depth at the Yucheng Experimental Station ranges from 1.5 to 4.0 m. The annual mean temperature is 13.1° in Yucheng, and the annual precipitation is 582 mm, of which 70 % occurs from June to September. There is a typical crop rotation of winter wheat (Oct.–Jun.) and summer maize (Jun.–Oct.) in the Yucheng region. However, precipitation does not meet crop water demand, especially for winter wheat, so irrigation is required to obtain a higher crop yield. Winter wheat commonly needs irrigation three times during its growing season (pre-frost, jointing, and shooting stages), whereas maize may need irrigation once or twice (seeding

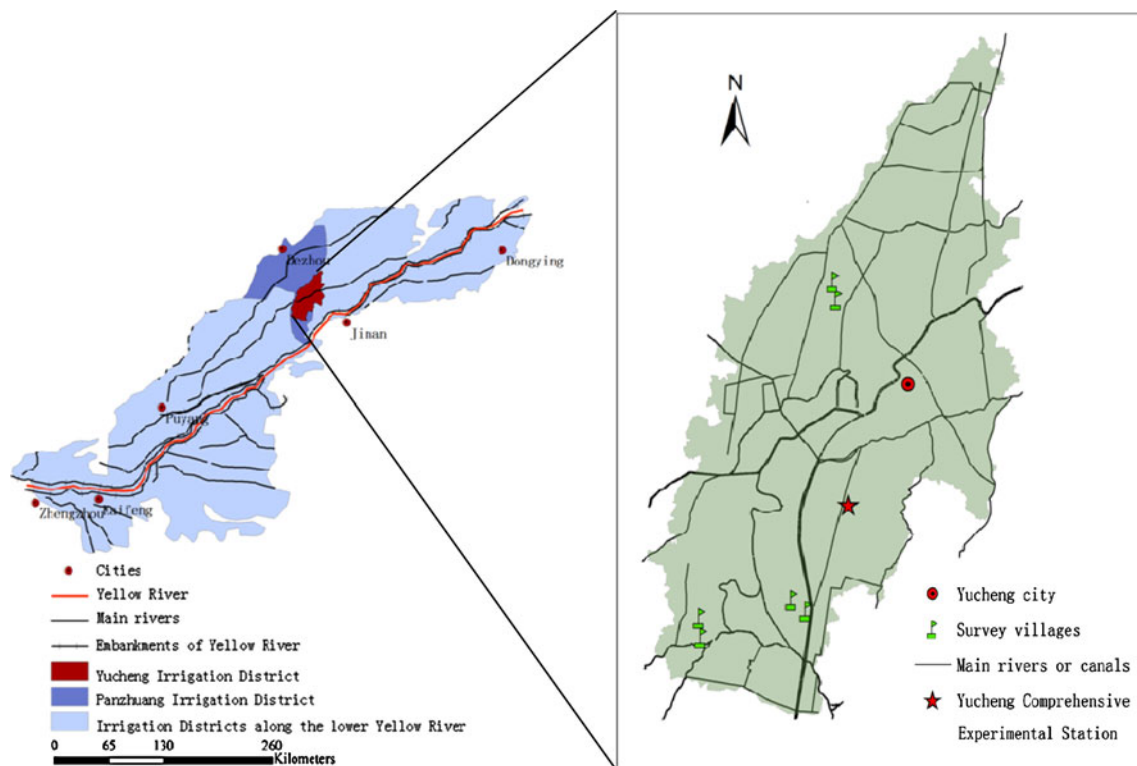


Fig. 1 Study area with major rivers and sample villages for agricultural irrigation survey

and jointing stages) or maybe not at all during its growing season.

A main canal delivering water from the Yellow River passes through the study area (Fig. 1). The ditch canal networks are dense, and agricultural irrigation is highly dependent on water from the Yellow River. The annual mean intake of water from the Yellow River amounts to 207 million m³ for agricultural practices in the Yucheng region. The Yucheng region can be divided into three different typical irrigation districts according to their water supplies: the gravity irrigation district (GID), the pumping irrigation district (PID), and the well irrigation district (WID). Border irrigation is widely used in all three irrigation districts.

Data used in this study

Agricultural irrigation survey

Two kinds of surveys, field surveys and farm household surveys, were conducted in 2 sample villages in each GID, PID, and WID in July of 2010 (Fig. 1, Table 1). The villages were chosen according to water supply conditions for irrigation. The information of border dimensions, irrigation supply, and hydraulic engineering was collected by field surveys. We also collected information on current irrigation management and investigated potential problems in irrigation by interviewing farmers and through written questionnaires.

Field experiment

Field experiments on winter wheat irrigation were conducted using 8 plots at the Yucheng Comprehensive

Experimental Station (37°10'N, 116°22'E), located in the study area. The experimental plots were irrigated at the stage of winter wheat jointing in 2009 or 2010, and field measurements were taken for existing border dimensions and for optimized border dimensions. The measurements that were collected were: (1) border dimensions, using measuring tape in the field; (2) border slopes, determined by averaging several measurements of border slope using an optical level along the length of the borders (the selected borders were very flat in two directions of border length and width, so border surface elevation was not measured and its effects on border irrigation was not considered in this study); (3) inflow rates, measured using a V-notch weir; (4) supply times, recorded using a stopwatch; (5) surface water advance progress, defined by recording the time when the surface water flow first reaches the benchmarks that were set up every 10 m along the border lengths before the irrigation; (6) basic soil intake rates, determined by averaging three measurements of basic soil intake rate using a double-ring infiltrometer; and (7) soil water profiles from the surface down to 1.0 m with an increment of 0.1 m, measured using a CNC503B neutron probe (Beijing Chao Neng Technology CO. LTD, Beijing, China), 24 h before and after irrigation. Two neutron probe access tubes were installed at the upper and the lower ends of fields in each of four experimental plots.

Detailed information of experimental plots and irrigation management is listed in Tables 2 and 9. Field trials were firstly conducted to calculate field characteristic parameters and to demonstrate the agreement between measured and simulated results with WinSRFR3.1. Other field trials were carried out after the borders had been optimized to evaluate the water savings from measured results.

Methodology

The framework of methodology used in this study is shown in Fig. 2. Details are described below.

Performance indicators for border irrigation

Three indicators were used in this study to evaluate the performance of border irrigation, D_{app} (the average depth applied to field), AE (application efficiency), and DU_{min}

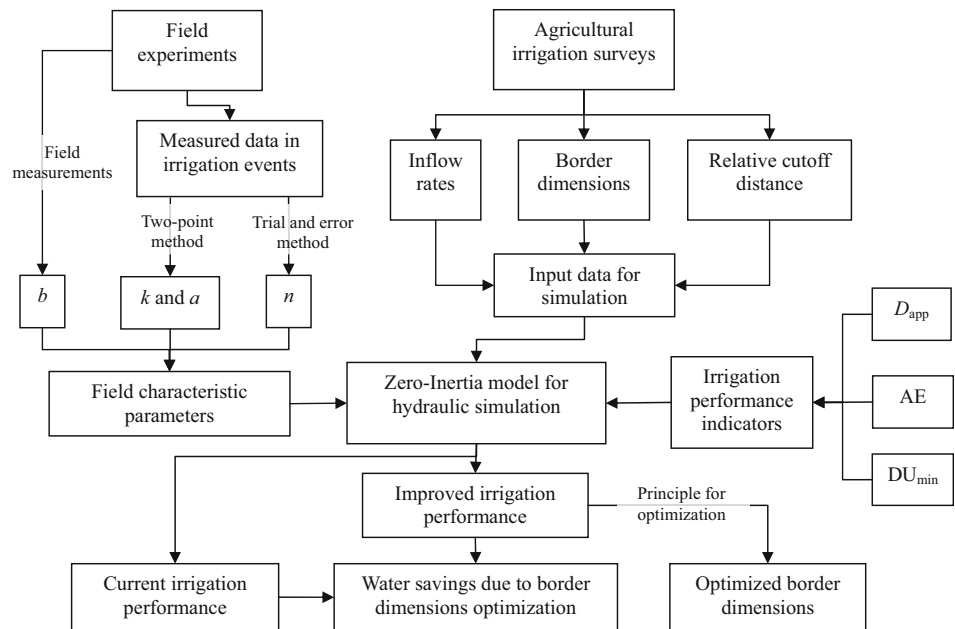
Table 1 Survey samples in the GID, PID, and WID

Irrigation district	Number of sample villages	Number of sample farm households	Number of sample borders	Total area of sample farm fields (ha)
GID	2	74	1,681	230.3
PID	2	64	1,312	151.7
WID	2	88	1,809	120.1

Table 2 Detailed information of experimental plots and irrigation management

Year	ID of borders	L (m)	W (m)	Q (l m ⁻¹ s ⁻¹)	T (min)	R	D_{app} (mm)	S_0 (m m ⁻¹)	b (mm h ⁻¹)
2009	1-1	200.0	7.7	4.73	108.0	0.92	153.5	0.0013	18.0
	1-2	200.0	6.5	5.87	69.0	0.85	121.5		
2010	2-1	200.0	8.0	4.35	98.0	0.85	127.8		
	2-2	194.0	5.4	5.60	77.0	0.82	133.4		

Fig. 2 Scheme for evaluating the approach for this study



(distribution uniformity of the minimum; Bautista et al. 2009b):

$$AE = \left(\frac{D_r}{D_{app}} \right) \times 100 \%, \tag{1}$$

$$DU_{min} = \left(\frac{D_{min}}{D_{app}} \right) \times 100 \%, \tag{2}$$

where D_r is the average depth added to the root zone storage, D_{min} is the minimum infiltrated depth along the length of fields.

Simulating with the WinSRFR3.1 package

WinSRFR is an integrated software package for analyzing surface irrigation systems, which combines the surface irrigation systems simulation program SRFR (Strelkoff et al. 1998), the design tool for sloping, open-ended border strip systems BORDER (Strelkoff et al. 1996), and the design tool for level-basin systems BASIN (Clemmens et al. 1995). Its latest version is WinSRFR3.1 released in 2009 (Bautista et al. 2009a, b). Users can analyze the field evaluation data, estimate the field infiltration properties, assess the performance of an observed irrigation event, suggest design and operational alternatives, test individual scenarios, and conduct sensitivity analyses. In this study, WinSRFR3.1 was used to obtain the estimate of field characteristic parameters and to simulate the hydraulic process and performance of border irrigation.

When estimating the field soil characteristic parameters, the infiltrated depth was calculated with a modified Kostikov formula (USDA-ARS 2009):

$$z = k\tau^a + b\tau + c, \tag{3}$$

where z is the infiltrated depth (mm) computed as a function of the intake opportunity time τ (h), k is coefficient constant representing the relative ease at which water infiltrate into the soil (mm h^{-a}), a is exponential constant describing the change in infiltration rate as the soil saturates with water, b is a parameter associated with the steady-state infiltration behavior (mm h^{-1}), and c is a storage term describing the instantaneous infiltration through macropores (in this study, $c = 0$).

Two solution models, the zero-inertia and the kinematic-wave models, are used by WinSRFR3.1 to conduct surface water hydraulic simulations. WinSRFR3.1 switches the solution model from the zero-inertia to the kinematic-wave when the bottom slopes exceed 0.004 (USDA-ARS 2009). Because the bottom slopes of our experimental plots were less than 0.004, only the zero-inertia model was used in this study (Walker and Skogerboe 1987):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} + \frac{\partial z}{\partial \tau} = 0, \tag{4}$$

$$\frac{\partial y}{\partial x} = S_0 - S_f, \tag{5}$$

where A is the cross-sectional flow area per unit width (m^2), Q is the discharge per unit width ($\text{l m}^{-1} \text{s}^{-1}$), y is the flow depth (m), t is the time elapsed since the start of the irrigation (h), x is the distance the water flow front has advanced along the border (m), S_0 is the slope of the border (m m^{-1}), and S_f is the friction slope obtained from the Manning formula (m m^{-1}).

In this study, WinSRFR3.1 is used to simulate the current and optimized irrigation performance with field measured data as inputs.

Calculation of field characteristic parameters

The field characteristic parameters referred to in this study include field roughness coefficient (n) and the infiltration parameters (k , a , and b). In the calculation of n , k , and a , the basic soil intake rate (b) needs to be known in advance, and its value was previously measured with a double-ring infiltrometer (Table 2).

This study adopted the Elliot-Walker two-point method (Walker and Skogerboe 1987) to estimate the infiltration function (Eq. 3) for the field. This method is a simple nonlinear optimization procedure for the calculation of soil infiltration parameters. It could be adopted directly (Yan and Li 2005) or be used to validate other methods (McClymont and Smith 1996).

The value of the parameter n was established by trial and error, which meant that an initial value was given to n at first, and k and a were calculated using the two-point method; surface water flow advance curves were then simulated with the zero-inertia model. The simulated advance curves were compared with the observed ones, a new value was given to n if the two curves did not fit well, and the above procedure was repeated until the two curves fit well; in this manner, the values of n , k , and a were confirmed. To avoid loss in local optimization and to obtain global optimal values of n , it was necessary to ensure that the values of n ranged from 0.02 to 0.40 when calculating because this was the basic range of the field roughness coefficient (Zhang et al. 2006).

Results and discussion

In this section, results of the agricultural irrigation surveys, parameter estimates, and simulation models are presented firstly. Then, the performance of current and optimized border irrigation systems is evaluated based on information from the surveys and experimental data, as well as the simulation model. Finally, the total water-saving potential of border irrigation in the Yucheng region due to border dimensions optimization is assessed.

Agricultural irrigation survey

Inflow rate

The inflow rate plays a principal role in improving the performance of irrigation, and its value greatly depends on the water source and pump performance during irrigation.

Table 3 Inflow rate from irrigation survey in the GID, PID, and WID

Irrigation district	T_{mean} (h)	Inflow rate	
		Q_0 ($\text{m}^3 \text{h}^{-1}$)	$Q_{0\text{mean}}$ ($\text{m}^3 \text{h}^{-1}$)
GID	1.3	60–120	90
PID	1.6	60–100	80
WID	3.1	30–50	40

In practice, the supply discharge amounts vary among the GID, PID, and WID (Table 3). There are few differences between the inlet discharges in the GID and PID, with a mean irrigation time of 1.3 and 1.6 h and a mean supply discharge of 90 and 80 $\text{m}^3 \text{h}^{-1}$, respectively. However, a larger difference is found between the above districts and the WID. The mean irrigation time in the WID is 3.1 h, and the mean inlet discharge is 40 $\text{m}^3 \text{h}^{-1}$.

The inlet discharge differences between the GID, PID, and WID are mainly due to the difference in local water supply conditions. In the GID, the farm ditch forking from the head ditch directly conveys water into farmlands when irrigating. Generally, the inlet discharge was large, and irrigators would not decrease the inflow rates. However, this situation did not occur in the PID and WID because water is pumped to fields. The water levels of the irrigation canals and ditches in the PID are relatively high, so water can be pumped easily onto farmlands. To obtain a large inlet discharge, farmers usually choose high-powered pumps. When water sources are wells, even high-powered pumps are not always sufficient for lower groundwater levels. Thus, the supply discharges in the WID are the smallest.

Border dimensions

Statistical analysis on border lengths and widths was conducted based on field survey data (Fig. 3, Table 4). For border lengths, there is no large difference in the distribution between the GID, PID, and WID. However, Fig. 3a demonstrates that the border lengths of the top 25 % quartile have the largest variation in the WID, with a mean of 101.0 m, compared with means of 78.8 and 64.0 m in the GID and PID, respectively. For border widths, large differences in the distribution between the GID, PID, and WID are demonstrated by comparing the mean border widths (W_{mean}) and the coefficient of variation of border widths (CV_W ; Fig. 3b, Table 4). The border widths within the WID show the most apparent central tendency, with the smallest W_{mean} of 5.2 m and the smallest CV_W of 25.6 %. In contrast, the border widths in the GID have the largest W_{mean} of 11.2 m and the largest CV_W of 49.7 %.

The differences in border dimensions between the GID, PID, and WID are mainly due to the diverse inlet

Fig. 3 The boxplots of border lengths and widths in all three irrigation districts

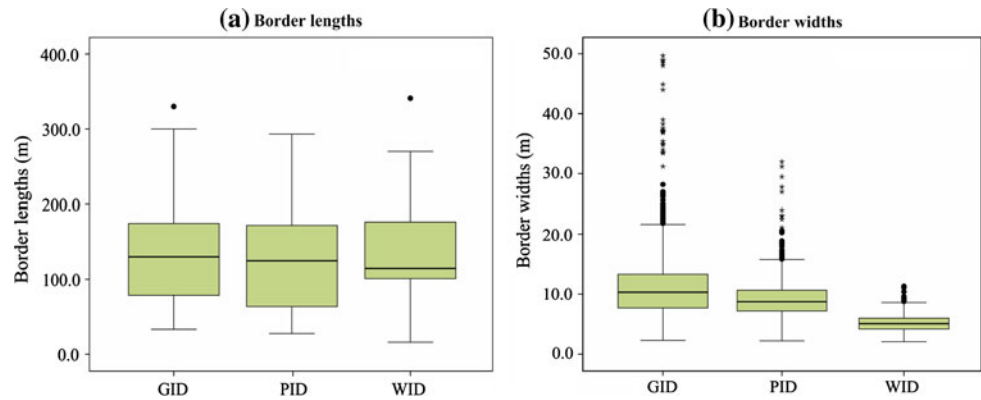


Table 4 Border dimensions from irrigation survey in the GID, PID, and WID

Irrigation district	Border dimensions									
	L_{min} (m)	L_{max} (m)	L_{mean} (m)	σ_L (m)	CV_L (%)	W_{min} (m)	W_{max} (m)	W_{mean} (m)	σ_W (m)	CV_W (%)
GID	33.3	330.0	133.1	66.65	50.1	2.3	49.7	11.2	5.57	49.7
PID	28.0	293.0	129.1	71.81	55.6	2.3	32.0	9.3	3.19	34.3
WID	16.0	341.1	132.2	60.01	45.4	2.1	11.3	5.2	1.33	25.6

Table 5 Relative cutoff distance from irrigation survey in the GID, PID, and WID

Irrigation district	GID	PID	WID
R	0.85–1.0	0.92–1.0	0.98–1.0

discharges. According to farm household surveys, most farmers like to practice simple irrigation management on large borders to save labor. Due to large supply discharges in the GID, farmers could extend the border width without affecting irrigation practices. The smallest supply discharges in the WID mean that farmers have to diminish the border widths to speed up surface water flow advances and to accomplish an irrigation event quickly.

Relative cutoff distance

Survey results suggest that farmers in different irrigation districts employ different irrigation management strategies (Table 5). It is found that farmers in the GID use a smaller relative cutoff distance, compared with those farmers in the PID and WID because of the differences in supply discharge. In the GID, the inlet discharges are large; thus, irrigators could cut off the water supply relatively early, and the surface water flow could still advance to the end of the borders. However, if the inlet discharges are cut off early in the WID, the surface water flow might not reach the borders because of smaller inlet discharges.

Parameters and model test

Field characteristic parameters

Based on field experiments, the values of field characteristic parameters (k , a , and n) for different plots were calculated (Table 6, Fig. 4). To evaluate the border irrigation systems in the Yucheng region using simulation software, it was necessary to choose representative values of field characteristic parameters. In this study, we averaged the four infiltration curves derived from the field experiments to obtain one infiltration curve and averaged the four field roughness values to obtain a mean value for field roughness.

Model test

Before the water hydraulic simulation, the irrigation requirements need to be known, which differs with local irrigation schedules, meteorological conditions, and soil

Table 6 Estimates of the field roughness coefficient and soil infiltration parameters

ID of borders	n	K (mm h ^{-a})	a	n_{ave}	k_{ave} (mm h ^{-a})	a_{ave}
1-1	0.16	72.734	0.575	0.12	85.483	0.520
1-2	0.07	100.557	0.464			
2-1	0.14	73.921	0.641			
2-2	0.11	98.773	0.403			

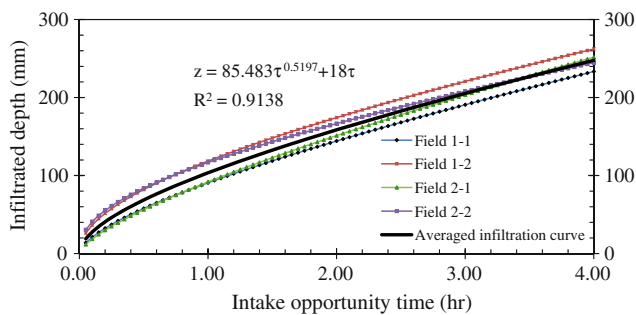


Fig. 4 The simulated infiltration curves and the averaged infiltration curve

moisture content. Based on local survey data and prior research (Zhao et al. 2002; Liu et al. 2009), the required application depth per irrigation event is 100 mm in the Yucheng region. Furthermore, the simulation of border irrigation was performed with the design factors and management conditions in Tables 2 and 6 as inputs.

Simulated water flow advance curves using WinSRFR3.1 were compared with the measured advance curves (Fig. 5). Results suggested that WinSRFR3.1 effectively simulated the hydraulic processes, that is, the advance of the surface water flow, although there were some points that deviated from the fitting curve due to the change in hydraulic conditions after the water supply stopped. The root mean square error resulting from simulated advance time and observed advance time was less than 1.0 min among the four irrigation events. This indicates that WinSRFR3.1 is able to calculate water savings

under specific field characteristic parameters in the study area, which makes up for the deficit of field experiments. To evaluate the performance of current and improved border irrigation systems, simulation with models is indispensable for various scenarios of irrigation management.

Evaluating the performance of current border irrigation systems

This study integrated irrigation management data (e.g., inlet discharges and border dimensions) with field characteristic parameters to simulate the present performance of border irrigation systems in the different irrigation districts in the Yucheng region. To simplify the simulation and assure the representativeness of the inputs, border length and width were set equal to the median values (Table 7), supply discharges were set equal to mean inflow rates (Table 3) in the GID, PID, and WID, and field roughness coefficients, field infiltration parameters (Table 6), field slopes, and basic soil intake rates (Table 2) were used as inputs. The required irrigation depth was 100 mm. The downstream outlet from the fields was assumed to be blocked during the simulations; moreover, it was required that the minimum infiltrated depth along the field length was greater than the required application depth.

Results of the current irrigation performance within the GID, PID, and WID were given in Table 7 (irrigation performance before border widths optimization). D_{app} was 169, 156, and 164 mm in the GID, PID, and WID,

Fig. 5 Results of the simulated and observed advances

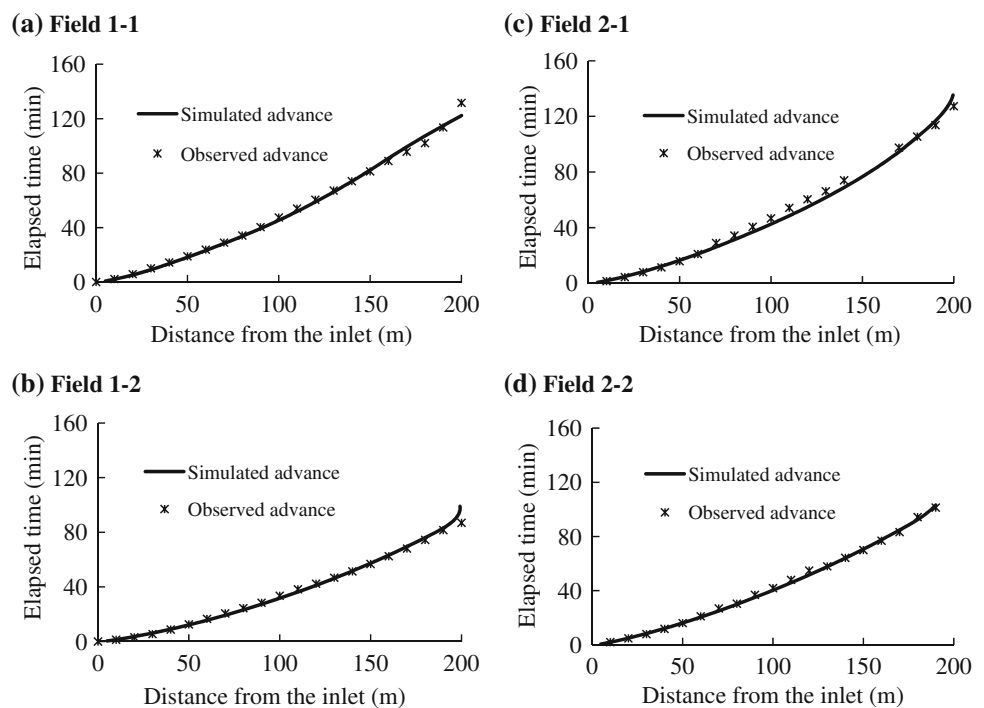


Table 7 The simulated performance of border irrigation before and after border width optimization in the GID, PID, and WID

Irrigation district	L_{med} (m)	Q_{0mean} ($m^3 h^{-1}$)	Before border width optimization						After border width optimization					
			W_{med} (m)	T (min)	R	D_{app} (mm)	DU_{min} (%)	AE (%)	W_{opt} (m)	T (min)	R	D_{app} (mm)	DU_{min} (%)	AE (%)
GID	130.0	90.0	10.3	150.5	0.97	169	59.2	59.1	5.5	54.2	0.89	114	88.1	87.9
PID	125.0	80.0	8.8	128.6	0.97	156	64.3	64.2	5	52.8	0.90	113	88.9	88.7
WID	114.7	40.0	5.1	144.4	0.98	164	60.7	60.6	3	59.3	0.92	115	87.2	87.1

respectively, which highly exceeded the required application depth by 69, 56, and 64 %. DU_{min} and AE for the GID, PID, and WID, respectively, were <65 %, which suggested a lower water use efficiency with a nonuniform infiltration distribution profile along the length of borders and more than one-third of the applied depths out of the field root zone. Generally, an improved surface irrigation system could achieve acceptable performance with DU_{min} and AE >80 % (Pereira et al. 2007), so the current border irrigation systems were practiced with poor performance in all three irrigation districts.

Over-irrigation commonly happens in all three irrigation districts. The water infiltration distribution profiles are nonuniform along the length of borders (Fig. 7, Table 7). This was a key reason for the low efficiency of irrigation, even though the minimum infiltrated depth was greater than 100 mm. For example, the infiltrated depth at the inlet end of plots reached 195 mm in the GID. When field characteristics and supply discharges did not change, over-irrigation at the inlet end was due to the small inlet discharges per unit width. Small inlet discharges per unit width slowed the advance of the surface water flow, and thus the opportunity times for infiltration at the inlet end were much greater than those at the outlet end.

The poor performance of current irrigation systems is greatly dependent on the combination of present inflow rate, mismatched border dimensions, and relative long cutoff distances. To improve the performance of border irrigation, optimizing any of these factors will improve irrigation performance.

Optimizing border dimensions and evaluating the performance of improved border irrigation systems

Optimizing border dimensions

Border dimensions in the GID, PID, and WID were optimized using WinSRFR3.1 in this study. The irrigation management in different irrigation districts was inputted as follows: supply discharges set equal to mean inflow rates (Table 3), field roughness coefficients and infiltration parameters (Table 6), field slopes, and basic soil intake rates (Table 2). The required depth of irrigation was 100 mm, and

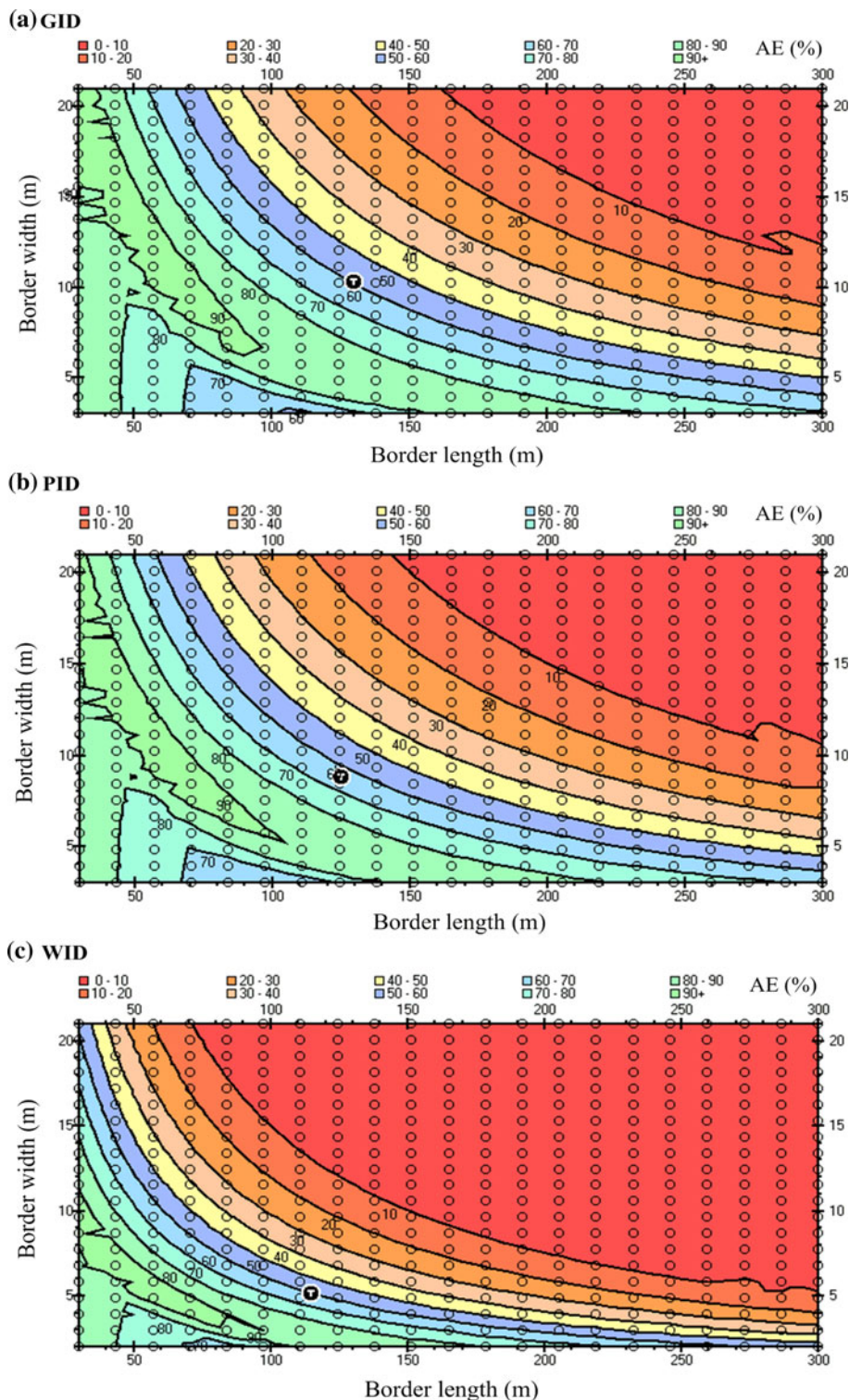
the downstream outlet from fields was assumed to be blocked during the simulations. The principle of optimization was that the minimum infiltrated depth along the length of borders was greater than the required application depth, and that the optimal AE should be greater than 80.0 %. According to Eqs. (1) and (2), when the simulated AE is >80.0 %, the D_{app} will be <125.0 mm with DU_{min} >80.0 % because the systems had no runoff losses. In this paper, we defined optimal border dimensions as border lengths and widths with irrigation performance of D_{app} <125.0 mm, AE >80.0 %, and DU_{min} >80.0 % under practical management. For simplicity, only the simulated AE for different border dimensions was compared in Fig. 6.

It was obvious that the optimal border dimensions in the GID, PID, and WID were different according to simulated AE (Fig. 6). Under the condition of AE >80.0 %, the corresponding distribution ranges of optimal border length and width in the GID and PID were larger than that in the WID, and the difference between that of the GID and PID was not clear. To improve the irrigation performance, two strategies were derived from the simulated AE within the GID, PID, and WID: one was to decrease border width to increase inlet discharge per unit width, and to promote the advance of surface water flow; and the second was to shorten border length to reduce the difference of intake opportunity time between the inlet and outlet ends to produce a more uniform infiltration distribution along the length of the border.

Considering local supply discharges, optimized border dimensions were presented in Table 8. For fields with short, moderate, or long length, the optimal border dimensions in the GID and PID were similar. However, the optimal border lengths in the WID were much smaller than those in the GID and PID, and the optimal border widths in the WID were approximately half of those in the GID and PID. Optimizing border dimensions in the GID, PID, and WID theoretically is necessary for the extension of this technology.

In our surveys, we found that some farmers have been optimizing border dimensions empirically to improve border irrigation performance. Other considerations were making irrigation management easier, obtaining higher yields, and controlling fuel charges for water pumping. Current border dimensions in different irrigation districts

Fig. 6 The simulated application efficiency (AE) for different border dimensions in the GID, PID, and WID



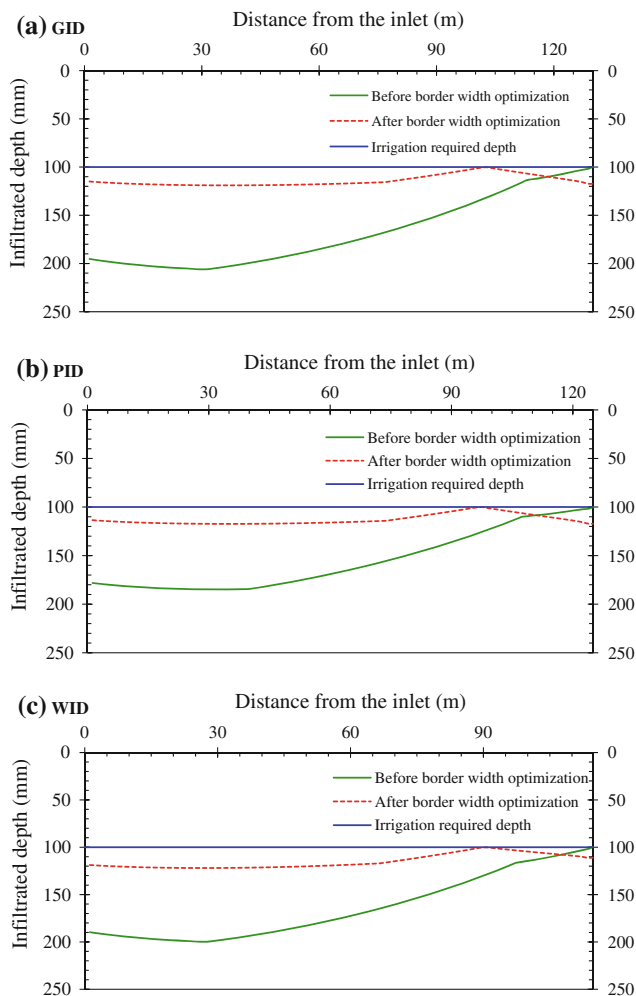
came from the trade-off between fuel charges and easier operation. In the GID and PID, field plots were generally large for the convenience of farming and irrigation operation without incurring extra fuel charges, while border dimensions in the WID were diminished to promote flow water advance to save fuel charges.

Evaluating the performance of improved border irrigation systems

To evaluate irrigation performance after border dimensions optimization, border widths were optimized according to the results in Table 8 with border lengths

Table 8 The optimized border dimensions within the GID, PID, and WID

Irrigation district	Optimized border dimensions					
	Short borders		Moderate length borders		Long borders	
	$L_{opt.}$ (m)	$W_{opt.}$ (m)	$L_{opt.}$ (m)	$W_{opt.}$ (m)	$L_{opt.}$ (m)	$W_{opt.}$ (m)
GID	<93	8–12	93–166	4–7	L/2	4–7
PID	<97	7–11	97–167	4–6	L/2	4–6
WID	<83	4–6	83–132	2–4	L/2	2–4

**Fig. 7** The simulated infiltration distribution before and after border width optimization within the GID, PID, and WID

unchanged. The improved irrigation performance was presented with D_{app} of 114, 113, and 115 mm in the GID, PID, and WID, respectively. DU_{min} and AE for all three irrigation districts were >85 % (Table 7). Compared to current irrigation performance (before border width optimization in Table 7), the D_{app} was reduced by 55, 43, and 49 mm for the GID, PID, and WID, respectively. Values

for DU_{min} and AE were increased by more than 24 % for all irrigation districts. Optimization of border width greatly improved border irrigation performance.

The infiltration distribution profiles along the length of borders after the optimization of border widths are shown in Fig. 7. After the border width optimization, infiltrated depths at the inlet ends sharply decreased to <120 mm, and percolation along the border lengths were reduced to <20 mm for the GID, PID, and WID. Compared to the infiltration distribution profiles before border width optimization, a large amount of water was saved to avoid deep percolation and the uniformity of infiltration distribution was significantly improved. This great change in the infiltration distribution profile led to the improvement of irrigation performance after border dimensions optimization.

The applied depths before and after border dimensions optimization from field trials are presented (Table 9). Compared to the mean applied depth of 142.3 mm before border dimensions optimization, a total volume of 30.8 mm of water was saved under the same relative cutoff distance. This result suggested that D_{app} decreased together with the reduction in border dimensions.

In summary, both simulation and field trials demonstrated that optimizing border dimensions is a promising method to improve border irrigation performance for small-scale farming practices in the lower Yucheng region (Liu and Cai 2002; Li and Rao 2003; Liu et al. 2005).

Assessing the water-saving potential of border dimensions optimization for border irrigation

To assess the potential annual water savings from all irrigation districts in the lower Yucheng region, an application depth of 125 mm and an application efficiency of 80 % were used for the estimated frequency of annual irrigation events. The amount of 125 mm was used because optimal border dimensions were defined with $D_{app} \leq 125$ mm and $AE \geq 80.0$ % in this paper. Irrigation frequency was determined from farm household surveys. The irrigation frequency of winter wheat was 2.1, 2.2, and 2.6, and that of

Table 9 The comparison of measured applied depth (D_{app}) before and after border dimensions optimization in field trials

Observed data	Year	ID of borders	L (m)	W (m)	Q ($l\ m^{-1}\ s^{-1}$)	T (min)	R	D_{app} (mm)	Mean of D_{app} (mm)
Before border dimensions optimization	2009	3-1	206.0	7.7	4.73	108.0	0.90	149.3	142.3
	2010	3-2	188.9	8.0	4.35	98.0	0.90	135.3	
After border dimensions optimization	2009	3-3	100.0	5.0	3.56	54.5	0.90	117.0	111.5
	2010	3-4	82.0	4.4	4.34	33.5	0.90	106.0	

Table 10 The annual water-saving potential of border dimensions optimization in the GID, PID, and WID in the Yucheng region

Irrigation district	D_{app} before optimization (mm)	D_{app} after optimization (mm)	Water-saving potential of D_{app} (mm)	Irrigation frequency of winter wheat (times)	Irrigation frequency of maize (times)	Irrigated area ($\times 10^3$ ha)	Annual water-saving potential ($\times 10^4$ m ³)	Total ($\times 10^4$ m ³)
GID	169	125	44	2.1	0.8	1.17	149.29	5,550.9
PID	156	125	31	2.2	0.7	25.23	2,268.18	
WID	164	125	39	2.6	1.8	18.26	3,133.42	

maize was 0.8, 0.7, and 1.8 in the GID, PID, and WID, respectively (Table 10). The irrigated area within all three irrigation districts in the Yucheng region was 1.17×10^3 , 25.23×10^3 , and 18.26×10^3 ha according to Bulletin of Yucheng National Economy and Social Development Statistics in 2008.¹

For the GID, PID, and WID, the water savings per irrigation event was calculated to be 44, 31, and 39 mm, and the AE was increased by 20.9, 15.8, and 19.4 %, respectively. The total water savings for the GID, PID, and WID was calculated by multiplying the water savings per irrigation event by the annual irrigation frequency and the gross irrigated areas. The sum of annual water savings in the GID, PID, and WID represented the total annual water savings in the Yucheng region. Results suggested that a total volume of $5,551 \times 10^4$ m³ could be saved annually in border irrigation by optimizing border dimensions in the Yucheng region (Table 10). This amount of water can support 1×10^5 people's living in this region of China (NBSC 2010).

Conclusions and perspectives

A practical and water-saving irrigation system is urgently required to relieve the lack of water resources in northern China under small-scale farming. For this purpose, the

potential of improving border irrigation performance through border dimensions optimization was evaluated on the irrigation districts along the lower Yellow River. Results indicate that mismatched existing irrigation system conditions, for example, supply discharge, border dimensions, and relative cutoff distance, lead to low irrigation performance. Based on field measurements, household surveys, and a simulation model, border dimensions were optimized. The optimal border dimensions in different irrigation districts were determined to be diverse. The performance of optimized border irrigation systems was greatly improved as shown with simulation models and field tests. The D_{app} within the GID, PID, and WID could be decreased to 114, 113, and 115 mm, respectively, and the AE could be increased to 87.9, 88.7, and 87.1 %, respectively. Taking into account the case study area of the Yucheng region, optimizing border dimensions can save approximately $5,551 \times 10^4$ m³ of water per year. This practical technology of optimizing border dimensions is being adopted by farmers using methods of trial and error, and it is one of the least costly, and most easily understood technologies for improving irrigation performance. It is worthwhile to encourage water savings by establishing standardized border dimensions in farming practices in the North China Plain. However, there are some existing barriers to extend this technology in some regions with very small field plots; it is difficult to merge small plots into large plots because of different land-use rights. Local governments need to consider current land-use policy in order to improve water-savings throughout this region.

¹ Bureau of Statistics of Yucheng in Shandong province, 2009. Bulletin of Yucheng National Economy and Social Development Statistics in 2008. Yucheng: Bureau of Statistics of Yucheng in Shandong province. (in Chinese).

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