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Research Paper

Field assessment of basin irrigation performance and water saving in Hetao, Yellow River basin: Issues to support irrigation systems modernisation

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Water-saving irrigation needs to be implemented in Hetao irrigation district to help satisfying the demand by other users in the Yellow River basin. Aiming at assessing the potential irrigation performance and water saving at farm level, a set of traditional basins and another of precision-levelled basins cropped with maize, wheat and sunflower and managed by farmers were evaluated. Data were collected to characterise the basin sizes, microtopography, inflow rates, advance and recession times, cut-off time and soil water content. In addition, families of infiltration curves were derived from field observations and subsequent use of model SIRMOD. Infiltration was higher for the precision-levelled basins and decreased from the first to the next irrigation events. Infiltration data were used to support the computation of distribution uniformity (DU), beneficial water use fraction (BWUF) and deep percolation (DP). For traditional basins, DU and BWUF were low and DP was high. When precise land levelling was practised, DU increased greatly to near 94% but BWUF improved little, because irrigation scheduling was inadequate leading to excessive water application; however, non-negligible water saving was achieved for maize and wheat since they have higher irrigation demand. In contrast, simulating the application of an appropriate irrigation scheduling through adjusting the cut-off time led to an approximately unchanged DU but BWUF greatly increased and DP reduced to 10% on average. This condition represents a potential water saving of 34–39%; however its achievement requires improved design of farm systems, appropriate irrigation water deliveries and scheduling, and the support and training of farmers.

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1. Introduction

The Hetao irrigation district (Hetao), located in the upper reaches of the Yellow River, is one of the largest irrigation districts of China, with 570,000 ha of irrigated land. The average annual rainfall is near 200 mm, so only irrigated agriculture is feasible. The canal network is supplied directly from the Yellow river. The Yellow River Water Conservancy Commission (YRWCC) is reducing diversions of Yellow river water to irrigate this area from 5.2×10^9 m^3 $year^{-1}$ to 4.0×10^9 m^3 $year^{-1}$ (Qu et al., 2003; Wang, Gao, & Lu, 2005), which implies the adoption of various water-saving technologies. This reduction is due to the increased demand for non-agricultural sectors and to reduced precipitation, probably due to climate change (Zhao, Xu, Huang, & Li, 2008), and aims to control the water scarcity conditions occurring in the middle and lower reaches of the Yellow river. Forecast scenarios on water resources allocation and use in the basin point to the need to reduce irrigation water use (Xu, Takeuchi, Ishidaira, & Zhang, 2002; Yu, 2006).

A variety of water-saving technologies is considered by Hetao and Inner Mongolia water managers (IWC-IM, 1999) aiming to reduce the agricultural demand for water, to improve environmental conditions, and to increase water productivity and farmers' incomes. These technologies consider the improvement of: (a) the water conveyance service, mainly through upgrading water delivery and reducing operational runoff wastage; (b) farm water use when implementing improved crop irrigation schedules with low to moderate deficit irrigation; and (c) farm surface irrigation, mainly through precise land levelling and upgraded technologies for furrowed and flat level basin systems. Impacts of these technologies in terms of irrigation performance, water saving and salinity control were analysed in previous studies applied to Huinong and Hetao irrigation systems (e.g., Deng, Shan, Zhang, & Turner, 2006; Gonçalves, Pereira, Fang, & Dong, 2007; Pereira, Gonçalves, Dong, Mao, & Fang, 2007; Xu, Huang, Qu, & Pereira, 2010, 2011).

Surface irrigation is the most appropriate irrigation method for Hetao because irrigation water is diverted from the Yellow River, which has a very high sediment concentration, averaging 3.1 kg m^{-3} at Dengkou, but reaching 5.17 kg m^{-3} (Wang & Cheng, 1993). These water quality conditions make it impossible to use sprinkler or microirrigation systems. In addition, favouring basin irrigation, land is flat, the conveyance and distribution network is designed and operated for surface irrigation, this method is appropriate to leach salts, and farmers have a good knowledge of the irrigation method they use. Modern technologies of surface irrigation, such as modernised furrowed and flat basin systems, precise land levelling and improved cut-off times, may well adapt to improve current practices and farmers have been shown to easily adopt them. The excessive use of water to control soil salinity is a major issue because farmers often over-irrigate for this purpose, despite it being known that autumn irrigation is generally sufficient to control salinity (Li et al., 2010).

Modern surface irrigation design applies simulation models, providing an increased quality of procedure because models allow the quantification of the integrated effect of numerous factors, such as field length and slope, soil infiltration and roughness, inflow discharge, land shape and surface microtopography (Clemmens, Walker, Fangmeier, & Hardy, 2007; Reddy, 2013; Strelkoff & Clemmens, 2007; Walker & Skogerboe, 1987). Nevertheless, in addition to hydraulics simulation, there is the need for a combined application of a variety of model tools for irrigation scheduling, land levelling, field distribution systems, and economic and environmental impacts analysis. Data requirements are therefore high and these data should be obtained as close as possible to actual field conditions, namely relative to infiltration characteristics. Benefits of modern surface irrigation could only be achieved if improvements in system design and irrigation scheduling were to be implemented together (Darouich, Gonçalves, Muga, & Pereira, 2012; Pereira, Oweis, & Zairi, 2002).

Land levelling plays a determinant role in the performance of surface irrigation, particularly in basin irrigation (Abdullaev, Hassan, & Jumaboev, 2007; Clemmens, Dedrick, Sousa, & Pereira, 1995; Dedrick, Gaddis, Clark, & Moore, 2007; Playan, Faci, & Serreta, 1996). Applications have been studied for North China and Hetao (Bai, Xu, Li, & Pereira, 2010, 2011; Li, Xu, & Li, 2001; Zheng, Shi, Guo, & Hao, 2011). Precise land levelling is particularly appropriate because it provides for significant reduction of the irrigation advance time and promotes uniformity of infiltration (Bai et al., 2010, 2011), thus favouring water saving and crop growth and yield; however, related benefits are not always tangible in terms of farm profitability, which explains why farmers may prefer the simpler and cheaper traditional land smoothing. Land levelling is traditionally performed in Hetao using rudimentary equipment and practices, with low quality and performance. Assessing present and improved land levelling conditions and related impacts on irrigation performance is therefore required to evaluate possible water savings and to base further decisions on irrigation improvements.

The performance of basin irrigation systems depends on the design, land levelling and farmers management, including the irrigation scheduling adopted, the inflow rate applied and the appropriateness of adopted cut-off time (Clemmens et al., 2007; Clyma & Clemmens, 2000; Pereira, 1999; Pereira et al., 2002). The importance of appropriate delivery schedules needs also to be considered as they constrain farm irrigation scheduling (Pereira et al., 2002). The traditional practice of over-irrigation in Hetao is explained by the need for salts leaching and to avoid any water deficits resulting from undesirable delays in water delivery, which are out of farmers' control; in addition, because the water fee relates to the field size and does not depend upon the volume of water use, there is no incentive for water saving. In contrast, adopting a limited deep percolation is desirable for maintaining the salts concentration at an appropriate level as previously analysed for the neighbouring areas of Huinong (Pereira et al., 2007; Xu et al., 2013). It is therefore also necessary to assess impacts of inflow rate control to support further improvements in Hetao.

Soil infiltration is a crucial factor impacting surface irrigation design and operation, namely the advance and recession and the distribution uniformity. Surface irrigation design and evaluation require quantification of soil infiltration characteristics, which can vary seasonally within a field and due to cultivation practices. Infiltration is difficult to predict with reliability and accuracy if appropriate field observations are not practised (Nie, Fei, & Ma, 2012; Walker & Skogerboe, 1987). Infiltration can be described by various equations and the respective parameters can be obtained with several types of field tests and by using intake families based on soil type or on basic infiltration rate (Walker, Prestwich, & Spofford, 2006). A commonly used infiltration equation is the Kostiakov equation (Walker & Skogerboe, 1987) whose parameterisation may be performed with volume balance or the inverse solution based on irrigation evaluation data (Darouich et al., 2012; Elliott, Walker, & Skogerboe, 1983; Holzapfel et al., 2004; Khatri & Smith, 2005; Strelkoff & Clemmens, 2007).

Taking into account the need to develop feasible solutions for water-saving irrigation in Hetao, particularly to provide for the modernisation of basin irrigation, a field study was undertaken in Dengkou area aimed at: 1) characterising traditional basin irrigation; 2) parameterising soil infiltration in relation to events considered and land levelling conditions; 3) evaluating performances of basin irrigation when adopting precise land levelling and flow-rate management; and 4) assessing water saving impacts of surface irrigation modernisation. Data and results should contribute to develop a knowledge database for design of modernised farm systems.

2. Material and methods

2.1. Characterising irrigation events

Field work has been developed at Dengkou, located in the upstream zone of Hetao, in the period 2012–2014. The study area is located within an irrigation sector where rotational delivery is practised as managed by a Water Users Association (WUA). Up to seven irrigation events per year can be practised in addition to the autumn irrigation. Typical field lengths vary between 50 m and 70 m and widths vary from 7 to 50 m. The soil is a silt loam with an average total available water of 200–260 mm m^{-1}. The main cultivated crops are wheat, maize and sunflower, these ones often intercropped with wheat. The field irrigation schedule depends upon the canal delivery operation, following the decisions of WUA relative to the supply of the secondary canals. The inflow rates and the cut-off time, i.e., the time duration of water application, followed the common farmers practice.

Two sets of fields were considered: (i) a set of eleven basins adopting traditional irrigation practices including land levelling, that were used to characterise the current irrigation conditions; and (ii) a set of six precise laser-levelled basins, used to assess impacts of improved irrigation practices. Irrigation and crop management were carried out by the farmers. A total of 51 irrigation events were evaluated.

The basin irrigation evaluations followed the procedures proposed by Merriam and Keller (1978) and Walker and Skogerboe (1987) and included the measurement of field microtopography, inflow rates, cut-off, advance and recession times, soil moisture prior to and after the irrigation and crop development. Inflow rates (q_{in}) were measured with trapezoidal weirs with observations every 5–7 min, which allow the inflow hydrographs and the cut-off times (t_{co}), i.e., the time duration of irrigation water application, to be obtained. The applied irrigation depths were obtained from integrating the inflow hydrographs, i.e., as the product of the average q_{in} by t_{co}. Soil moisture was measured by the gravimetric method with soil sampling at two locations, at 15 m from the upstream end of the basin and at 15 m from the downstream end. Samples were collected for each 20 cm soil layer down to 80 cm depth. Soil samples were collected every 7–10 days and on the days before and after irrigation. Soil water content data were used with the soil water balance model ISAREG (Pereira, Teodoro, Rodrigues, & Teixeira, 2003) to estimate the required depths at time of each irrigation event. The use of this model for various crops in Hetao has been reported by Zheng, Shi, Cheng, Zhu, and Goncalves (2010).

The advance and recession times (t_{adv} and t_{rec}) were measured with the help of a grid of stakes located every 10 m in the longitudinal direction, and placed in two to three tiers depending upon the basin width. The advance times were recorded when water reached these observation stations while recession times were recorded when water fully infiltrated the soil at the same stations; however, when the unevenness of the soil surface caused the water to pond for a very long time, t_{rec} were recorded when water disappeared from the ground near to the station. The infiltration opportunity time (τ) was calculated for each station from the advance and recession times ($\tau = t_{rec} - t_{adv}$).

A microtopography survey was performed using a 5 × 5 m grid in all fields using an electronic level sensor (KGU9901, Chongqing Shanlan, China) having an elevation accuracy of 1 mm; observations were performed before and after the land levelling operations. The land levelling operations consisted of the common traditional practice of land smoothing, using small graders and disc harrows coupled with a scraper, or a precise zero levelling using a grading blade controlled by a Spectra Precision Laser (AG401, Trimble, USA). This operation was performed by October, after field ploughing and before the autumn irrigation. To assess the quality of land levelling, the root mean of squared deviations between observed and target land elevations ($RMSD_{EL}$) was used:

$$RMSD_{EL} = \sqrt{\frac{\sum_{i=1}^{N}\left(Obs_i - Tag_i\right)^2}{N}} \tag{1}$$

where Obs_i and Tag_i ($i = 1, 2, \ldots, N$) are respectively the observed and the target land elevations.

2.2. Soil infiltration

Following previous research (Zheng, Shi, Zhu, Liu, & Gonçalves, 2009), soil infiltration was studied using the Kostiakov equation (Walker et al., 2006)

$$Z = K \cdot \tau^{a} \tag{2}$$

where Z is cumulative infiltration depth (m); τ is infiltration time (min), K ($m\ min^{-a}$) and a (dimensionless) are empirically adjusted parameters. In basin irrigation, different from furrow or border irrigation because the duration of the water application is relatively short, the intake rate derived from Equation (2), does not significantly underestimate infiltration at the end of irrigation (Walker et al., 2006). Thus, there is no need to consider a third parameter representing the basic infiltration rate, which is also confirmed with results shown for basins by Pereira et al. (2007), Zheng et al. (2009) and Nie et al. (2012).

Field tests were performed using a basin infiltrometer (Walker & Skogerboe, 1987) to produce a first estimation of the parameters K and a. These parameters were later adjusted using field advance and recession observations through the application of the inverse method (Horst, Shamutalov, Pereira, & Gonçalves, 2005; Katopodes, Tang, & Clemmens, 1990; Zhang, Xu, Li, & Cai, 2006) with the simulation model SIRMOD (Walker, 1998).

The Manning's hydraulic roughness coefficients n used for these simulations were obtained from a earlier field study in the same area where n was computed from observations of discharge and flow depth (Zheng et al., 2009). A review of literature (e.g. Mailapalli, Raghuwanshi, Singh, Schmitz, & Lennartz, 2008; Pereira et al., 2007; Reddy, 2013; Sepaskhah & Bondar, 2002; Strelkoff, Clemmens, & Bautista, 2009) supported the assumption that the parameter n essentially depends upon the roughness of the surface as dictated by tillage and plant density and development but not upon the land slope. Sepaskhah and Bondar (2002) reported that the impact of furrow slope on n was not statistically significant. Thus, impacts of laser levelling on the n variability were not considered when simulating modernised basins because tillage and crops were the same as for traditional basins. Larger n values were assumed for basins cropped with wheat (n varying from 0.18 to 0.20 $m^{-1/3}$ s) because vegetation is more dense for this crop than for maize and sunflower, where n varied from 0.14 to 0.16 $m^{-1/3}$ s. The values of n were assumed to slightly increase from the first to the last irrigation due to increased roughness when plants develop (Pereira et al., 2007). However, impacts of n values on simulated basin irrigation performances may be small as referred to by Reddy (2013) and as shown by Nie et al. (2012) when simulating the advance in borders.

The infiltration parameter values were obtained through the inverse mode simulation with the SIRMOD model (Walker, 1998, 2005), fitting observed advance and recession data to obtain the K and a parameters. This was performed through an iterative minimisation of the sum of the square roots of the mean squared deviations (SRMSD) between observed and simulated advance and recession times defined as:

$$SRMSD = \sqrt{\frac{\sum_{i=1}^{N}(O_{ai} - S_{ai})^2}{N}} + \sqrt{\frac{\sum_{i=1}^{N}(O_{ri} - S_{ri})^2}{N}} \quad (3)$$

where O_{ai}, S_{ai}, O_{ri}, and S_{ri} (i = 1,2, … …, N) are respectively the times (min) observed and simulated for advance and for recession, which are identified respectively by the subscripts a and r, and N is the number of observations. This inverse mode procedure using SIRMOD has been often applied for furrows (Gillies & Smith, 2005; Gillies, Smith, & Raine, 2007; Walker, 2005) and basins (Darouich et al., 2012; Pereira et al., 2007). In the current study, the procedure was applied to every irrigation event evaluated, relative to both traditional and modernised irrigation, hence assigning a specific infiltration curve to each event aiming at calculating the performance indicators relative to each one.

The ensemble set of infiltration equations obtained in Dengkou for the total of 51 events was aimed at characterising infiltration in basins having a poor or a precise land levelling condition; thus, following the approach reported by Walker et al. (2006), it was also aimed to build typical infiltration families for silt loamy soils when used together with infiltration data available for Dengkou (e.g., Zheng et al., 2009).

2.3. *Performance indicators*

The performance indicators considered in this study consist of the distribution uniformity (DU, %), the beneficial water use fraction (BWUF, %) and the deep percolation ratio (DP, %) Following the approaches of Burt et al. (1997) and Pereira, Cordery, and Iacovides (2012) they are defined as follows:

$$DU = \frac{Z_{lq}}{Z_{avg}} \times 100 \quad (4)$$

$$BWUF = \begin{cases} \dfrac{Z_{req}}{D} \times 100 & Z_{lq} > Z_{req} \\ \dfrac{Z_{lq}}{D} \times 100 & Z_{lq} < Z_{req} \end{cases} \quad (5)$$

where Z_{req} is the average depth (mm) required to refill the root zone in the quarter of the field having a higher soil water deficit; D is the average water depth (mm) applied to the irrigated field; Z_{lq} is the average low quarter depth of water infiltrated in the field (mm); and Z_{avg} is the average depth of water infiltrated in the whole irrigated field (mm). Z_{req} was estimated from field measurements of the soil water content before the irrigation and refer to the soil moisture deficit in the root zone. Z_{lq} and Z_{avg} were estimated from computing the depth of water infiltrated during the infiltration opportunity time τ relative to each measurement station. D was computed as the product of the cut-off time by the average inflow rate. In basin irrigation, when runoff does not occur, as for the present application, $D = Z_{avg}$ and $DP = 100 - BWUF$.

3. Results

3.1. *Characterising traditional basin irrigation*

The size and topographic characteristics of traditional basin fields are presented in Table 1. Lengths range 52–68 m and widths range 7–25 m. It can be noticed that the magnitude of the cross slope is not negligible, with 5 out of 11 fields having a cross slope higher than 2.5‰. In practice, it results in a quicker advance at the lower side, hence delaying the advance in the upper side and reducing the infiltration uniformity. This is a consequence of the low performance of the traditional land levelling operation that does not provide for a proper levelling close to the field borders. Also noticeable is the fact that 5 out of 11 fields have a negative longitudinal slope, which induces a slow advance, longer irrigation cut-off time and larger water use, as well as ponding that is likely to correspond to slower

Table 1 – Characteristics of traditional basins.

Field identification	Crop	Length (m)	Width (m)	Transversal slope (‰)	Longitudinal slope[a] (‰)	Number of irrigation events evaluated
M-1	Maize	60	23	1.3	0.39	4
M-2	Maize	60	15	2.2	−0.14	4
M-3	Maize	60	10	−2.6	−0.03	4
M-4	Maize	60	21	0.6	−0.06	4
W-1	Wheat	65	19	−6.6	−0.23	4[b]
W-2	Wheat	68	14	−0.1	0.43	4[b]
W-3	Wheat	63	7	6.4	0.22	4[b]
W-4	Wheat	52	15	3.2	0.58	4[b]
S-1	Sunflower	67	18	−4.9	0.26	3[b]
S-2	Sunflower	50	25	−1.8	0.20	3[b]
S-3	Sunflower	68	16	1.4	−0.09	3[b]

[a] Negative slopes refer to conditions when the elevation at downstream end is higher than at upstream.
[b] Only the inflow rate and the cut-off time were observed when evaluating the first irrigation event.

infiltration. It was observed that all the fields have a relatively high downstream end due to deposit of sediments carried by the irrigation water, which tends to be higher where velocity reduces, and thus occurs at the downstream end. This also results in faster recession by the downstream quarter of the field (Fig. 1) and leads to a reduced infiltration opportunity time, thus to low uniformity of infiltration along the basin length.

Figure 1 shows the advance, recession and infiltration depth curves relative to selected field evaluation events. Advance curves vary due to topographic conditions downstream while recession curves vary much more, due to both the uneven microtopography and the unfavourable conditions downstream; t_{rec} tends to be higher by 3/4 or half length of the field, decreasing to the downstream end. Therefore, the infiltration opportunity time ($\tau = t_{rec} - t_{adv}$) varies greatly along the basins and, consequently, infiltration is quite uneven as evidenced in Fig. 1.

Table 2 shows data on observed inflow rates, required irrigation depths, and advance, recession and cut-off times relative to various basins. The inflow rates per unit width of the basins (q_{in}, l s^{-1} m^{-1}) were highly variable through the crop season. They were less variable for the maize fields, with q_{in} averages ranging 1.0–1.3 l s^{-1} m^{-1} with small standard deviations (sd) of 0.1–0.2 l s^{-1} m^{-1}. For wheat fields, larger q_{in} were observed, with means ranging 2.0–2.4 l s^{-1} m^{-1} and high sd (0.4–0.9 l s^{-1} m^{-1}). For sunflower fields, the average q_{in} decreased from the first to third irrigation event, from 2.4 to 1.6 l s^{-1} m^{-1}, with sd also decreasing from 0.5 to 0.2 l s^{-1} m^{-1}. However, there was no evidence that inflow rates relate to the crop cultivated in the various basins because q_{in} depends upon the discharge made available at the upstream end of the farm when water is delivered.

The required application depths Z_{req} increased throughout the irrigation season (Table 2), probably because intervals between irrigations changed little while the evapotranspiration demand generally increased from the first to the last irrigation event. Z_{req} for wheat increased in average from the second to the last irrigation from 48 mm to 55 mm, for maize it increased from 53 to 77 mm and for sunflower it also increased from 47 to 58 mm.

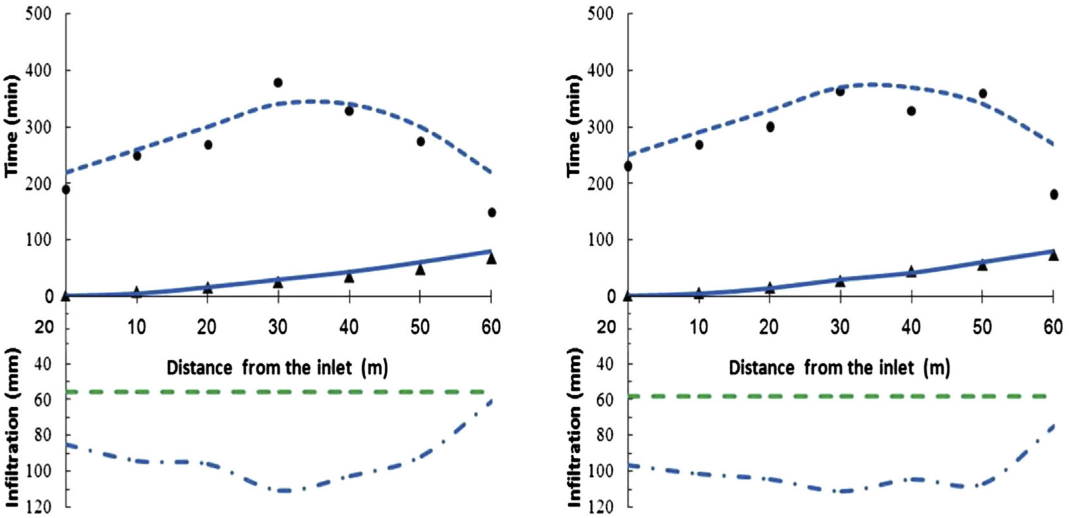
The advance time was smaller when the inflow rate was larger. The recession time varied considerably through the crop season with the average t_{rec} ranging between 278 and 493 min. This variability relates to the cut-off time and the unevenness of the soil surface. The infiltration opportunity time also varied much as influenced mainly by the recession time. The cut-off times (t_{co}) varied mainly with the crop due to differences in the inflow rate and the required application depths (Table 2). For wheat, t_{co} ranged from 27 to 88 min, for sunflower t_{co} varied between 38 and 56 min, and for maize ranged 63–124 min; t_{co} for maize showed the largest values, probably because farmers know that, among all three crops, maize has the highest crop water requirement and is less tolerant to salinity.

3.2. *Characterising modernised basin irrigation*

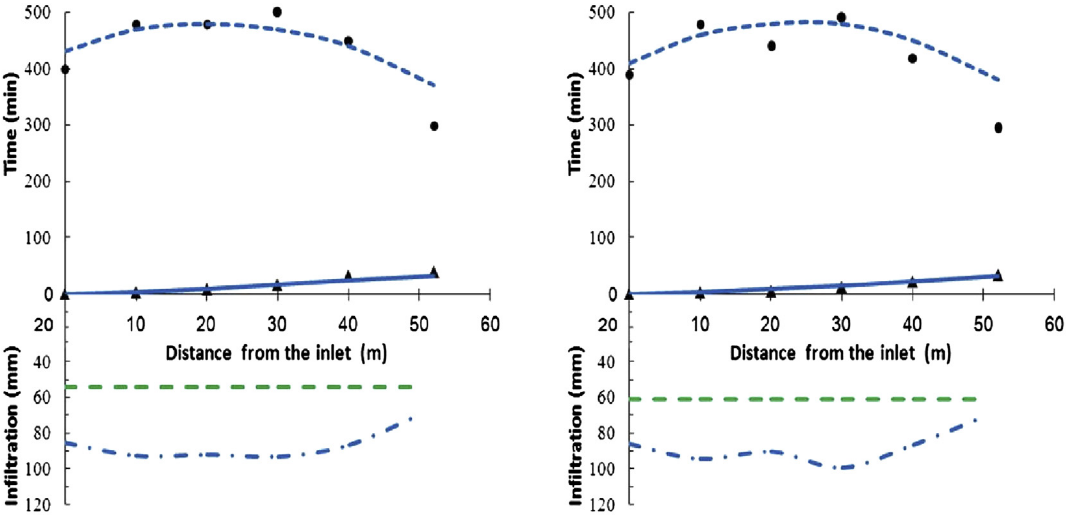
The main characteristics of the precise zero slope levelled basins are presented in Table 3. Basin lengths (50 m) did not change among evaluated basins but widths varied from 10 to 48 m. The $RMSD_{EL}$, characterising the elevation differences between actual and zero slope elevations, were small, with four out of six having $RMSD_{EL} < 3.0$ cm.

Inflow rates decreased from the first to the third irrigation events and were larger for wheat and smaller for maize (Table 4). However, a relationship between q_{in} and the cultivated crop was not considered. These q_{in} values were larger than for the traditional basins, which contributed to improve the irrigation performances analysed below. However, they show large variability (Table 4). The observed advance times (Table 4) varied inversely to the inflow rates; t_{adv} showed relatively small variation among basins and events, which is likely to be due to the favourable impact of the precise levelling. The recession times were much smaller than those observed in traditional basins and varied little among basins and events, also due to the favourable impact of the precise levelling. Consequently, the infiltration opportunity time also varied little among basins and events (Table 4). Results also show that t_{rec} increased when both the inflow rate and t_{co} increased, i.e., when the volume applied was larger.

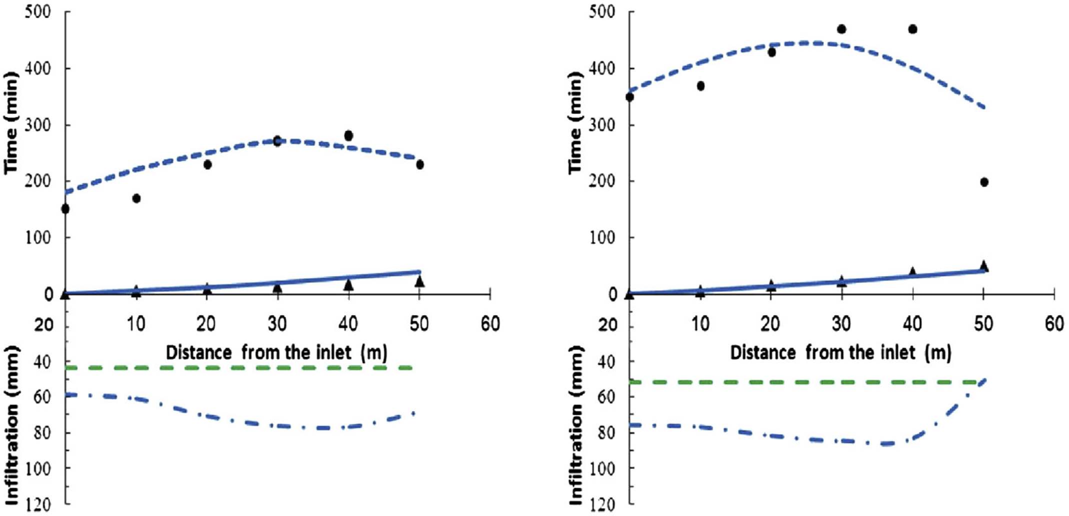
Advance and recession times are presented in Fig. 2 for selected evaluation examples. The advance curves are quite regular while the recession curves tend to parallel the advance curves, thus resulting in infiltration opportunity times that



a) M2-1, $Z=0.0051t^{0.50}$, SRMSD=43 min b) M2-2, $Z=0.0048t^{0.49}$, SRMSD=44 min



c) W4-2, $Z=0.0048t^{0.48}$, SRMSD=38 min d) W4-3, $Z=0.0049t^{0.48}$, SRMSD=47 min



e) S2-2, $Z=0.0050t^{0.49}$, SRMSD=33 min f) S2-3, $Z=0.0048t^{0.47}$, SRMSD=65 min

Fig. 1 – **Observed advance (▲) and recession (●), simulated advance (—) and recession (---); required irrigation depth (- - -) and estimated infiltration depth (-·-) of selected traditional basins cropped with maize (M, a and b), with wheat (W, c and d) and with sunflower (S, e and f). The infiltration equation used for estimating the infiltration depths and the SRMSD values relative to fitting advance and recession are also included.**

Table 2 – Traditional basin irrigation: average and range of inflow rates; required application depths; cut-off times, advance and recession times and infiltration opportunity time.

Irrigation event	Crop	Inflow rate (l $s^{-1}m^{-1}$)	Required depth (mm)	Cut-off time (min)	Advance time (min)	Recession time (min)	Infiltration opportunity time (min)
1	maize	1.0 (0.9–1.1)		106 (95–124)	82 (69–97)	351 (264–424)	318 (235–393)
	wheat	2.1 (1.3–3.2)		56 (27–88)			
	sunflower	2.4 (1.9–3.0)		41 (38–46)			
2	maize	1.1 (0.9–1.3)	53 (36–68)	79 (70–89)	70 (56–90)	322 (277–379)	292 (244–354)
	wheat	2.0 (1.5–2.5)	48 (38–59)	51 (38–76)	47 (34–73)	447 (407–496)	426 (391–462)
	sunflower	1.8 (1.5–2.0)	47 (44–50)	41 (38–45)	33 (24–42)	279 (222–317)	264 (210–299)
3	maize	1.3 (1.1–1.6)	67 (53–80)	72 (63–85)	65 (60–68)	389 (272–449)	362 (243–421)
	wheat	2.4 (1.4–3.9)	55 (51–61)	45 (30–65)	41 (28–70)	493 (428–584)	476 (408–572)
	sunflower	1.6 (1.3–1.8)	58 (52–65)	51 (46–56)	48 (46–50)	409 (304–505)	397 (300–493)
4	maize	1.1 (0.8–1.4)	77 (70–86)	99 (73–115)	80 (65–94)	438 (364–527)	404 (321–496)
	wheat	2.1 (1.8–2.8)	55 (44–75)	35 (30–38)	42 (37–53)	278 (247–360)	259 (229–344)

In the first irrigation event, only inflow rate and cut-off time were accurately observed; the required depths were not measured in the first irrigation.

Table 3 – Irrigation experimental field on modernised basins (zero slope precise land levelling).

Field identification	Crop	Length (m)	Width(m)	$RMSD_{EL}$ (cm)	Number of irrigation events evaluated
M-1	Maize	50	15	4.1	3
M-2	Maize	50	20	3.8	3
M-3	Maize	50	30	2.9	3
M-4	Maize	50	48	2.8	3
W-1	Wheat	50	10	2.7	3
S-1	Sunflower	50	15	2.9	2

$RMSD_{EL}$ is the root mean of squared deviations between observed and target land elevations.

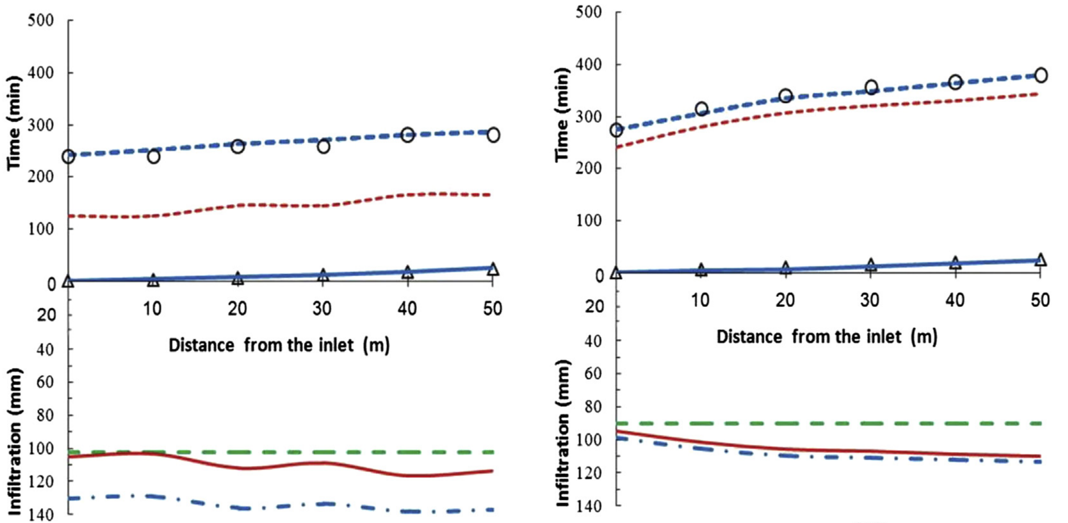
Table 4 – Characteristics of basin irrigation in precise zero levelled fields: average and range of unit inflow rates, required application depths, and cut-off, advance, recession and infiltration opportunity times observed and adjusted to apply the required depths.

Irrigation event	Crop	Inflow rate (l $s^{-1}m^{-1}$)	Required depth (mm)		Cut-off time (min)	Advance time (min)	Recession time (min)	Infiltration opportunity time (min)
1	Maize	2.2(1.6–2.8)	102 (93–110)	Obs	51 (40–62)	32 (23–44)	244(196–276)	230(184–262)
				Adj	44 (33–56)	32 (23–44)	180(145–205)	166(133–186)
1	Wheat	3.8	92	Obs	29	19	204	195
				Adj	21	19	124	115
1	Sunflower	2.4	55	Obs	36	23	300	290
				Adj	21	23	116	106
2	Maize	1.9(1.4–2.5)	99 (87–111)	Obs	50 (35–63)	35 (25–48)	298(257–318)	282(234–301)
				Adj	48 (33–61)	35	289(241–338)	272(220–326)
2	Wheat	3.6	57	Obs	25	25	216	204
				Adj	16	25	97	84
2	Sunflower	2.1	77	Obs	40	28	347	334
				Adj	30	28	202	189
3	Maize	1.7(1.4–2.6)	114(104–124)	Obs	67 (40–80)	33 (22–42)	357(325–396)	342 (311–374)
				Adj	61 (38–71)	33	333(311–370)	318 (297–360)
3	Wheat	3.3	88	Obs	30	22	286	276
				Adj	25	22	207	196

"Obs" and "Adj" stand respectively for times observed and adjusted to apply the required irrigation depths.

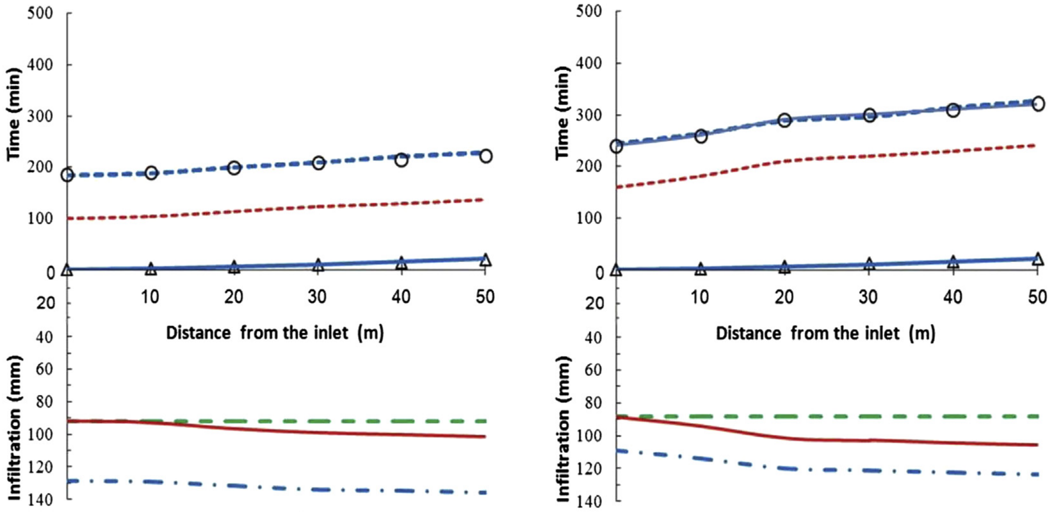
were similar when comparing up- and downstream sections of the fields. These performance characteristics are expected in precise levelled basins, having a small $RMSD_{EL}$ (Table 3), thus in agreement with results reported by Bai et al. (2010, 2011). Hence, the infiltration depth profiles were nearly uniform, much less uneven than those observed for the traditional basins (cf. Fig. 1 and Fig. 2).

When aiming at water saving, it is required to control t_{co} to adjust the infiltrated depth to the required depth, eventually considering a leaching fraction. The simulated impact of that



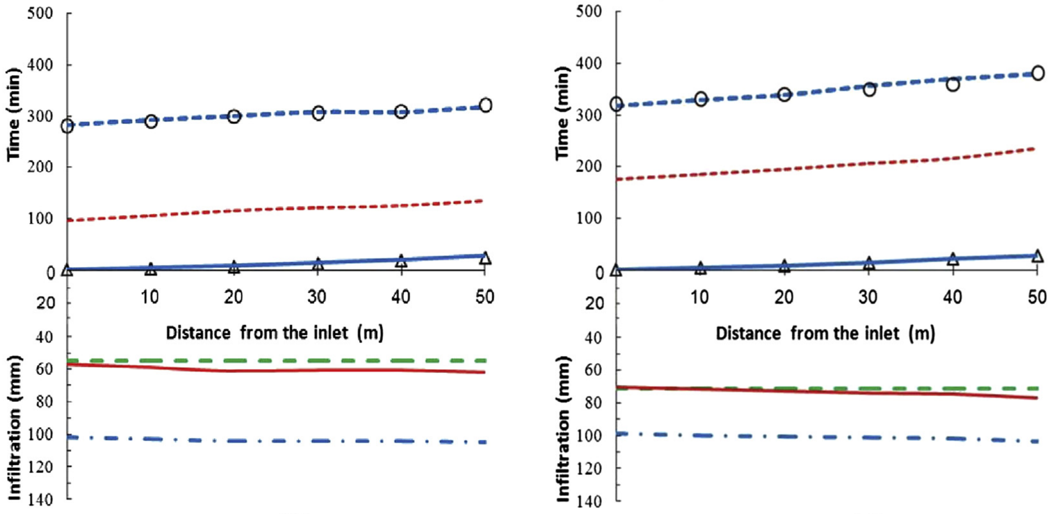
a) M1-1, Z=0.0050t$^{0.63}$, SRMSD=8 min

b) M1-2, Z=0.0045t$^{0.55}$, SRMSD=16 min



c) W1-1, Z=0.0058t$^{0.65}$, SRMSD=17 min

d) W1-3, Z=0.0053t$^{0.55}$, SRMSD=12 min



e) S1-2, Z=0.0053t$^{0.52}$, SRMSD=13 min

f) S1-3, Z=0.0048t$^{0.52}$, SRMSD=18 min

Fig. 2 – Observed (Δ) and simulated (—) advance, observed (O) and simulated (- - -) recession, simulated recession when the cut-off time is adjusted (-----), required infiltration depths (- - -), observed infiltration (· –), simulated infiltration depth when the cut-off time is adjusted (—) relative to modernised basins cropped with maize (M, a and b), wheat (W, c and d) and sunflower (S, e and f). The infiltration equation used for estimating the infiltration depths and the SRMSD values relative to fitting advance and recession are also included.

adjustment of t_{co} is shown in Fig. 2, both in terms of reducing t_{rec} and the infiltrated depth. This type of simulation is helpful when it is desired to improve irrigation scheduling and advising farmers about the quantity to apply, i.e., the best combination of both q_{in} and t_{co}. It may be observed that, despite the referred adjustment, Z_{avg} generally exceeds Z_{req} (Fig. 2) but the resulting over-irrigation is relatively small and may be reasonable to leach salts.

The relationships between t_{co} adjusted to provide for an improved irrigation management and t_{adv} are shown in Fig. 3a for various ratios t_{co}/t_{adv} considering several inflow rates. Results in this figure show that the t_{co}/t_{adv} ratio must be higher, 1.5 to 2, when inflow rates are low ($q < 1.6 \text{ l s}^{-1} \text{ m}^{-1}$), and smaller, 1 to 1.5, when higher inflow rates are considered. These results may be used as a practical rule to support deciding the cut-off time to adopt when a model is not used. Nevertheless, t_{co} depends of the required application depth and field length, increasing with both differently from the advance time. The relationships between t_{co} and t_{rec} are somewhat similar (Fig. 3b): the ratio t_{rec}/t_{co} varies between 7 and 10 for high inflow rates ($q_{in} \geq 2.5 \text{ l s}^{-1} \text{ m}^{-1}$), 4 to 8 for medium q_{in} ($1.6 \text{ l s}^{-1} \text{ m}^{-1} \leq q_{in} \leq 2.5 \text{ l s}^{-1} \text{ m}^{-1}$), and 4 to 5 for low inflow rates ($q_{in} < 1.6 \text{ l s}^{-1} \text{ m}^{-1}$). These results also show that the recession time increases with both the cut-off time and the inflow rate, i.e., with the volume of water applied at each irrigation; moreover, t_{rec} depends greatly upon the infiltration rate of the soil.

3.3. *Infiltration characteristics*

The infiltration parameters of the Kostiakov equation for all events evaluated (Table 5) were determined by the inverse method using the SIRMOD model as described in Section 2.2. The fits of the observed recessions in traditional basins were less good due to the varied shape of the recession curves (Fig. 1). These resulted in SRMSD often greater than 40 min. In contrast, good matches of both the advance and recession curves were obtained for the precise levelled basins (Fig. 2) with SRMSD averaging 16 min only.

The infiltration curves obtained from data collected in the traditional and modernised basins are compared in Fig. 4 while the respective parameters are presented in Table 5. These curves were used to compute the infiltrated depths in the various traditional and modernised basins as shown in Figs. 1 and 2. Results in Fig. 4 and Table 5 show that the infiltration was higher in the precision zero levelled basins relative to the traditional basins. Various factors may have contributed to these results. On the one hand, the adoption of a zero slope and the improvement of the microtopographic conditions of the basins definitely changed recession and, very likely, the resulting infiltration conditions associated with shorter and more uniform recession. This behaviour may be seen by comparing Figs. 1 and 2. On the other hand, it was noticed that drainage conditions were improved in the precision zero levelled basins because ponding was avoided; since ponding is associated with a retardation of the infiltration, i.e., with a lower infiltration rate, the non-occurrence of ponding is associated with improved infiltration rates in these silty soils. The studies by Bai et al. (2010 and 2011) show that the infiltration is impacted by the unevenness of the basin land levelling, particularly by the spatial variability of basin microtopography, which increases with the former and is likely associated with the occurrence of ponding. These studies, which included performing a detailed analysis of the spatial variability of infiltration, allow the inference that the cumulative infiltration in silty soils improved with the increased precision of the adopted land levelling.

Results in Fig. 4 and Table 5 also show that infiltration decreased from the first to the following irrigation events, particularly for the precision levelled basins. This behaviour may be explained by the processes occurring in the soil of the basins following water application. In particular, it is well known that erosion and deposition occurs in surface irrigation: soil erosion occurs when the flowing water detaches and transports soil particles while sedimentation occurs when the fluid transport capacity decreases to less than the sediment load (Trout & Neibling, 1993). This process is more important in furrows than in basins because the shear of the overland flow against the soil, which is a primary factor determining channel transport capacity and provides the detachment force, is larger in furrows than in basins or borders. Sedimentation of the detached particles reduces infiltration due to clogging of

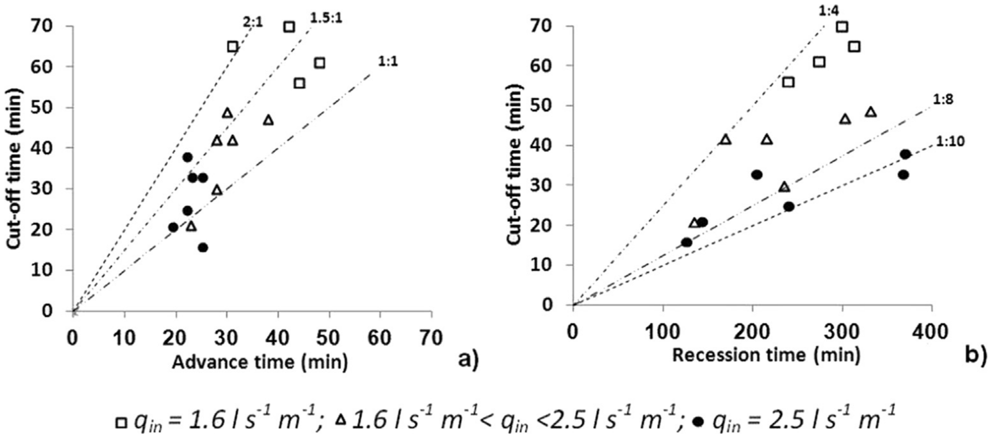


Fig. 3 – Relating the adjusted cut-off time with (a) the advance time and (b) the recession time for various inflow rates and ratios between cut-off time and respectively the advance and the recession time.

Table 5 – Kostiakov infiltration parameters relative to traditional and modernised basins.

Crop-field -event	K (m min$^{-\alpha}$)	a (–)	Crop-field-event	K (m min$^{-\alpha}$)	a (–)	Crop-field-event	K (m min$^{-\alpha}$)	a (–)	Crop-field-event	K (m min$^{-\alpha}$)	a (–)
Traditional basins											
M-1-1	0.0050	0.52	M-1-2	0.0050	0.51	M-1-3	0.0049	0.49	M-1-4	0.0050	0.50
M-2-1	0.0051	0.50	M-2-2	0.0048	0.49	M-2-3	0.0048	0.48	M-2-4	0.0050	0.49
M-3-1	0.0050	0.53	M-3-2	0.0049	0.50	M-3-3	0.0049	0.49	M-3-4	0.0051	0.48
M-4-1	0.0053	0.52	M-4-2	0.0051	0.49	M-4-3	0.0050	0.48	M-4-4	0.0049	0.49
–	–	–	W-1-2	0.0053	0.43	W-1-3	0.0049	0.45	W-1-4	0.0048	0.46
–	–	–	W-2-2	0.0045	0.50	W-2-3	0.0045	0.47	W-2-4	0.0048	0.47
–	–	–	W-3-2	0.0047	0.46	W-3-3	0.0049	0.48	W-3-4	0.0048	0.46
–	–	–	W-4-2	0.0048	0.48	W-4-3	0.0048	0.48	W-4-4	0.0047	0.47
–	–	–	S-1-2	0.0049	0.47	S-1-3	0.0048	0.48	–	–	–
–	–	–	S-2-2	0.0050	0.49	S-2-3	0.0048	0.47	–	–	–
–	–	–	S-3-2	0.0052	0.48	S-3-3	0.0049	0.47	–	–	–
Modernised basins											
M-1-1	0.0050	0.63	M-1-2	0.0045	0.55	M-1-3	0.0046	0.50	–	–	–
M-2-1	0.0053	0.62	M-2-2	0.0050	0.53	M-2-3	0.0043	0.52	–	–	–
M-3-1	0.0054	0.58	M-3-2	0.0050	0.54	M-3-3	0.0053	0.54	–	–	–
M-4-1	0.0055	0.57	M-4-2	0.0055	0.54	M-4-3	0.0050	0.55	–	–	–
W-1-1	0.0058	0.66	W-1-2	0.0053	0.57	W-1-3	0.0053	0.56	–	–	–
–	–	–	S-1-2	0.0053	0.52	S-1-3	0.0048	0.52	–	–	–

M stands for maize, W for wheat and S for sunflower. The first figure refers to the basin field number and the second identifies the irrigation event, e.g., M-3-2 refers to the second irrigation of field 3 cropped with maize.

surface soil pores. The process occurs in all irrigation events but varies from the first to the last (Trout, 1996). Thus infiltration varies from the first to the following events (Childs, Wallender, & Hopmans, 1993). A different approach to observe seasonal changes in furrow irrigation is described by Cameira, Fernando, and Pereira (2003) who reported a well defined trend of decreasing soil porosity. Macroporosity, which was the main contributor to the flow within the soil, decreased abruptly after the first irrigation and this led to reduced infiltration. A decrease in infiltration after the first event has been observed in various studies, e.g., Horst, Shamutalov, Gonçalves, and Pereira (2007) and Gonçalves, Muga, Horst, and Pereira (2011) in furrow irrigation while Pereira et al. (2007), Bai et al. (2010) and Darouich et al. (2012) reported reduction after the first irrigation in the case of basins and borders. In the case of traditional, poor levelled basins, due to their irregular and microtopography, that variation from the first to the following events was less evident.

The infiltration curves for all traditional and modernised basins in combination with infiltration data collected and analysed, allowed setting representative infiltration curves for Dengkou (Fig. 5) considering two types of soil infiltration curves that can be further used as default data for design of improved basin irrigation systems in Dengkou: i) high, where the curve SC-I refers to the 1st event, SC-II to the second and SC-III to the third and latter events; ii) medium, where the 1st event is now represented by the curve SC-III, the SC-IV relative to the 2nd event and the SC-V referring to the third and latter events.

3.4. *Irrigation performance of traditional and modernised basins*

The irrigation performance indicators relative to the traditional systems are shown in Table 6. The distribution uniformity ranged 56–73% but average values varied less, from 60 to 69%. That small variability of DU is due to the fact that DU essentially depends upon the characteristics of the irrigation system and less on the irrigation management, as analysed by Pereira et al. (2002). In fact, the traditional systems tend to behave similarly, particularly relative to t_{adv}, t_{rec} and, consequently, relative to the unevenness of infiltrated depths because these variables largely depend upon the basins microtopography and surface unevenness, which did not vary much among the evaluated basins.

The beneficial water use fraction, which corresponds to the formerly used application efficiency term, is a characteristic of management and is constrained by DU, which is a characteristic of the system (Pereira, 1999). Comparing Equations (4) and (5), it is evident that BWUF cannot increase above DU. Consequently, BWUF varied in a wider range than DU, from 38% to 73% (Table 6). The overall average was 62%. These results clearly show the limitations of traditional irrigation when aiming at modernising irrigation and achieving water saving and controlling salinity. Since operational losses are due to deep percolation, results clearly identify the need to control DP to improve BWUF and provide for water saving. This improvement requires a combination of precise land levelling, aimed at uniform water infiltration, and appropriate irrigation scheduling while adopting appropriate inflow rates and better targeted time duration of irrigation events, i.e., well adjusted cut-off times. However, it happens that the delivery schedule adopted by the Water Users Association in charge of the canal system management leads to delayed water applications relative to crop water demand, which does not favour the adoption of an appropriate irrigation scheduling. Improving the delivery scheduling is therefore a must.

Basin irrigation performance indicators relative to precise land levelled basins are presented in Table 7. Both Indicators

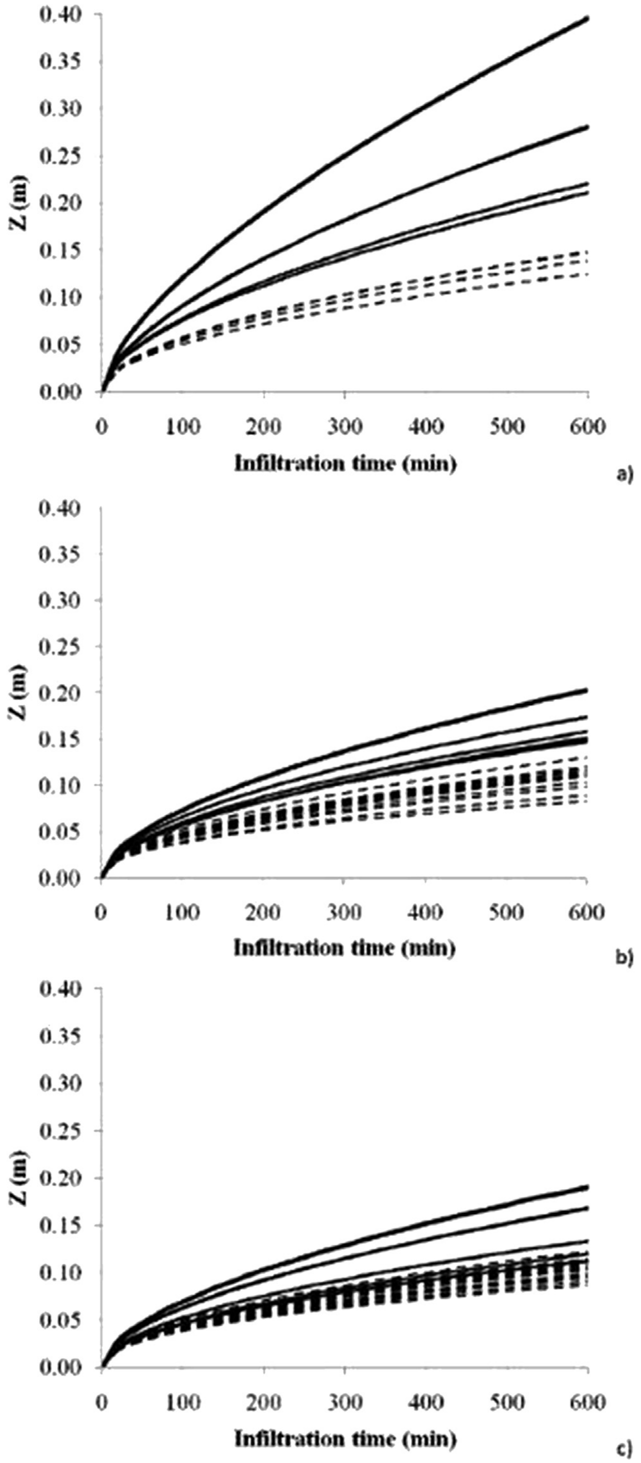


Fig. 4 – Observed cumulative infiltration curves for traditional (dashed lines) and modernised (continuous line) basins relative to: a) 1st event, b) 2nd event, c) 3rd event.

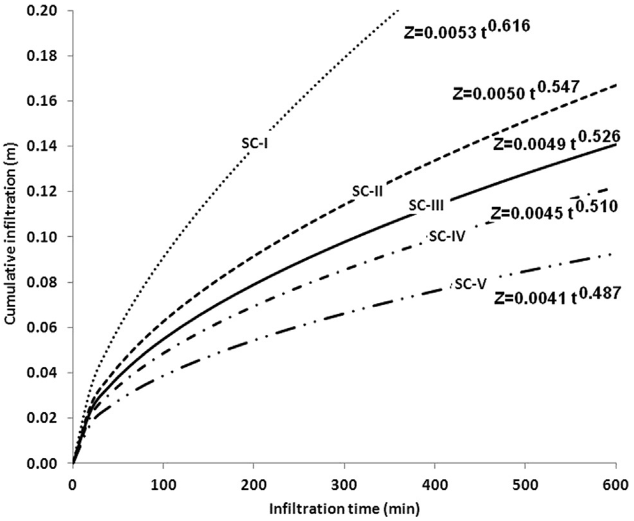


Fig. 5 – Standard cumulative infiltration curves for Denkou relative to a high infiltration soil (SC-I, 1st event, SC-II, 2nd event, SC-III, 3rd and 4th events); and to a low infiltration soil (SC-III, 1st event, SC-IV, 2nd event, SC-V, 3rd and 4th events).

are computed from field evaluations and are referred as “observed” and “potential”, the latter obtained from simulations relative to adjusting the cut-off time. Precise land levelling caused DU values to increase greatly for modernised basins relative to those of traditional irrigation. Observed DU ranged from 90 to 98% while the potential ones show similar values because changes in t_{co} have only a small impact on the uniformity of infiltration when land is precisely levelled. Lower values refer to less precise land levelling. In contrast, there is a large difference between observed and potential BWUF: observed values ranged 53–90% (Table 7), with lower values corresponding to excessive t_{co}, thus excess water application and high DP. This fact relates to the constraints imposed by the delivery schedule as referred to above. The potential values are higher and varied in a smaller range, from 87 to 92%, because when t_{co} is adjusted considering the inflow-rate available and the soil water deficit at time of irrigation, the infiltrated depths can approach the required depths, if DP is well controlled, and water saving may be achieved.

Attaining the potential BWUF values is difficult because farmers tend to over-irrigate; the traditional knowledge of

Table 6 – Observed averages and ranges of the performance indicators DU and BWUF[a] relative to traditional basins for various irrigation events and crops.

Irrigation event	Crop	DU (%)	BWUF (%)
First	maize	60 (56–62)	(no data)
Second	maize	64 (60–66)	59 (38–66)
	wheat	67 (61–72)	54 (44–61)
	sunflower	68 (60–73)	66 (61–73)
Third	maize	68 (64–71)	65 (60–71)
	wheat	64 (60–67)	59 (50–65)
	sunflower	69 (65–71)	67 (63–69)
Fourth	maize	68 (62–71)	65 (57–70)
	wheat	62 (56–68)	60 (52–66)

[a] DU and BWUF are respectively the distribution uniformity and the beneficial water use fraction.

Table 7 – Comparison of the observed and potential average and range values of the performance indicators DU and BWUF[a] relative to precise levelled basins for various irrigation events and crops.

Irrigation event	Crop	DU (%)		BWUF (%)	
		Observed	Potential	Observed	Potential
First	maize	96 (93–97)	96 (94–97)	79 (76–86)	89 (87–90)
	wheat	92	94	69	90
	sunflower	95	95	53	88
Second	maize	97 (94–98)	97 (95–99)	87 (83–90)	90 (88–91)
	wheat	90	90	53	88
	sunflower	95	97	70	91
Third	maize	97 (95–98)	97 (97–98)	88 (85–90)	90 (87–92)
	wheat	91	91	74	90

[a] DU and BWUF are respectively the distribution uniformity and the beneficial water use fraction.

farmers calls for applying large water depths because the next irrigation may be delayed due to constraints of the delivery schedule which depend on the decisions of the WUA managers. This is particularly important in the case of maize since it has low tolerance to salinity and to water stress. Thus, on the one hand, it is necessary to train the farmers to properly adjust t_{co} to soil moisture conditions, basin size and inflow rate available; on the other hand, it is required to train the system management staff to improve the water distribution service.

Results in Tables 6 and 7 show that performance indicators change from the first to the last irrigation event and vary with the crop. The variation with event is due to the fact that infiltration decreases from the first to the third irrigation event as analysed in Section 3.3 (Figs. 4 and 5). The variation with crops relates to crop water requirements and the way farmers schedule the respective irrigation, but also vary from the first to the last irrigation events due to infiltration conditions.

Aiming at defining future scenarios for improved basin irrigation, based upon results in Tables 6 and 7, the average of the considered indicators comparing actual and potential conditions are presented in Table 8. These results show that: (a) DU is expected to increase from the actual value of 60% to the potential 95% for the first irrigation, where the infiltration rate is high, and ranging from 66% to 95% when all irrigation events are considered; (b) BWUF may increase from the actual 60% to the potential 90% relative to all irrigation events; and (c) DP could then decrease from the actual average of 40% to a potential value of only 10% when all irrigation events are considered.

These results clearly indicate that basin irrigation has the potential to achieve considerable control over operational water losses when precise zero slope levelling is adopted and t_{co} is adjusted following the irrigation scheduling requirements. The potential DU values reported above exceed those referred to by Bai et al. (2011) for longer basins, with 100 m length, but may be achieved in shorter basins of 50 m length with zero slope if t_{co} is effectively adjusted and the unit inflow rate is 2.5 l s^{-1} m^{-1} or larger, as referred. The small potential DP referred above may contribute to control salinity and may be achievable as reported by Xu et al. (2013).

When DU could be improved and DP could be well controlled, high water saving may be achieved as shown in

Table 8 – Actual and potential performance indicators relative to traditional and modernised basin irrigation.

Performance indicator	First irrigation event		2nd And following irrigation events		All irrigation events	
	Actual (Traditional basins)	Potential (Modernised basins)	Actual (Traditional basins)	Potential (Modernised basins)	Actual (Traditional basins)	Potential (Modernised basins)
DU (%)	60	95	66	95	64	95
BWUF (%)	58[a]	89	62	90	60	90

[a] Estimated value.

Table 9 – Irrigation water saving in modernised basin irrigation.

	Maize	Wheat	Sunflower
Average irrigation water use at present (mm)	534	434	435
Irrigation water use in precise zero levelled basins (mm)	366	352	368
Water saving due to precise land levelling (mm)	168	82	67
Irrigation water use in levelled basins, with cut-off time adjusted (mm)	350	265	267
Additional water saving (mm)	16	87	100
Total water saving (mm)	184	169	167
Relative water saving (%)	34	39	39

Table 9. The potential water saving due to adopting precise land levelling and an adequate inflow rate averaged 168 mm for maize, 82 mm for wheat and 67 mm for sunflower in the current study. Water saving is expected to be higher for maize, where excess water is more often applied. It may be explained by the fact that farmers, knowing that this crop has a larger irrigation demand and lower tolerance to salinity, tend to irrigate to excess. If farmers apply an appropriate irrigation scheduling, thus properly adjusting the cut-off time to apply the required irrigation depths, then additional water saving are achieved. The potential water saving may then increase to 184 mm in case of maize, 169 mm for wheat and 167 mm for sunflower. These savings represent 34–39% of present seasonal irrigation water use. However its achievement requires appropriate training and support to farmers and not only improved technological and modelling approaches.

4. Conclusions

The performance of traditional basin irrigation in Hetao was assessed through field evaluation of 11 farm managed basins cropped with wheat, maize and sunflower and a total of 34 irrigation events. To support an appropriate computation of the performance indicators, infiltration curves were derived from field data and from the observed advance and recession curves, the latter through the inverse modelling approach aimed to minimise differences between observed and simulated values. Similar approaches were used for a set of 6 precise zero levelled basins consisting of 17 irrigation events. Thus, families of infiltration curves were obtained for the first, the second and the subsequent irrigation events for both the traditional and the precise levelled basins. It was observed that infiltration in the latter was not only more uniform but occurred at higher rates than in traditional basins.

In traditional basins, field evaluations did show that land levelling was very poor, unit inflow rates were small and cut-off times were excessively long. Hence, the advance and recession times were quite long and the recession curves were very irregular, thus resulting in non-uniform infiltration and a low DU ranging from 56 to 73%. These unfavourable conditions lead farmers to over-irrigate, mainly for maize, which produced high deep percolation and quite low BWUF. This farmer behaviour is understandable because the delivery schedule adopted by the WUA is not adequate, with deliveries delayed relative to the crop demand, resulting in crop water stress, which leads farmers to apply excess water to have it stored in the soil in anticipation of a next delivery being delayed.

The field evaluations of precise land levelled basins showed quite good DU, above 90%, but low BWUF, ranging from 56 to 90%. These results evidenced the limitations of adopting only precise land levelling. Simulations based on the observed data have shown that high BWUF and low DP can be achieved if inflow rates are large enough to produce a quick advance, and the cut-off times are adjusted to reduce application depths to values required to refill the root zone at time of irrigation. It may be concluded that good performance and high water saving may be achieved with basin irrigation in Hetao if improved land levelling, inflow rates and cut-off times are adopted in combination with adequate irrigation scheduling practices, which are constrained by the WUA adopted delivery schedule. Moreover, achieving these requirements is only possible if appropriate training and support are provided to the farmers, namely to help them changing from traditional to modern irrigation management, and a good interaction between farmers and WUA is developed that allows an appropriate irrigation scheduling program to be implemented.

Acknowledgements

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