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Research Article

Strategies to Improve the Irrigation Efficiency of Raised Beds on Small Farms

Ghani Akbar[1], Steven Raine[2], Allen David McHugh[3], Greg Hamilton[4] and Qurban Hussain[5]

[1]Climate Change, Alternate Energy and Water Resources Institute (CAEWRI), National Agricultural Research Centre (NARC), Islamabad, Pakistan; [2]National Centre for Engineering in Agriculture (NCEA), University of Southern Queensland (USQ), Toowoomba, Australia; [3]CIMMYT–China, Ningxia Academy of Agric. and Forestry Sciences, Yinchuan, P.R. China; [4]Maximum Soil & Water Productivity Pty Ltd. Perth WA, Australia; [5]Natural Resources Division, Pakistan Agriculture Research Council, Islamabad.

Abstract | The suboptimal irrigation management on small raised beds farms in the Indus Basin is considered to reduce irrigation efficiency and exacerbates waterlogging and salinity. Addressing this issue, farmer managed irrigations on commonly used Narrow Bed (NB) with furrow spacings 66 cm and newly introduced Wide Bed (WB) with furrow spacing 130 cm on sandy clay loam, were investigated using the irrigation modelling software, WinSRFR, to explore irrigation management strategies for improving irrigation eficiency. The study revealed existing average application efficiency of low quarter (*AE lq*) 71%, 87%, distribution uniformity of low quarter (*DU lq*) 70%, 80% and adequacy of low quarter (*AD lq*) 100 %, 90% for NB and WB, respectively. Majority (67%) of WB irrigations monitored were under irrigated while large number (50%) of NB irrigation were over irrigated. Simulation modelling showed that achievement of above 90% Potential Application Efficiency (PAE) is possible by improving operation (inflow rate and time to irrigation cut-off) and field design (field length and width/number of furrows per set). This work raised the prospects of improved irrigation efficiency of raised beds in Indus Basin, which may be possible without incurring any costs associated with altered infrastructure, new or modified machinery, or increased labour.

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***Correspondence** | Dr Ghani Akbar, CAEWRI-NARC, Park Road, Chak Shahzad Islamabad, Pakistan; **Email:** ghani_akbar@hotmail.com
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Introduction

The Indus Basin in Pakistan is one of the largest contiguous canal irrigation systems in the world (Qureshi and Barrett-Lennard, 1998). It comprise of a network of snowmelt river fed canals, distribution channels and water courses in sequence. Irrigation scheduling on farms is on weekly fixed turn basis known as "*warabandi system*". Generally the turn period and inflow rate vary from 2 to 4 hr ha^{-1} and 20 to 30 ls^{-1} respectively (Bandaragoda and Ur Rehman 1995; Akram and Mendelsohn, 2016). The traditional flat basin irrigation system cause excessive application losses. Now, due to growing awareness and desire for improving the crop water productivity on farms, the flat basin irrigation is gradually being replaced by bed-furrow irrigation system commonly known as raised beds (Akbar et al., 2016). The raised beds in Pakistan is characterised by short field length (~100m), small farm size (1 to 2 ha), intensive pre-sowing cultivation and variable bed and furrow sizes. Bed-furrow sizes depends on available machinery, crop type and farmer preferences. Generally, narrow beds (NB) or ridges (65-75cm furrow

Table 1: *Experimental site conditions during two irrigation events, on three sites in Mardan, northwest Pakistan*

Site No.	Crop	Growth Stage	Irrigation	Field length (m)	Remarks
1	Cotton	Flowering	3rd & 4th	86	Beds shallow cultivated before sowing
2	Maize	Establishment	1st & 2nd	90	Beds shallow cultivated then rotary hoeing conducted
3	Maize	Flowering	5th & 6th	90	Beds shallow cultivated then rotary hoeing conducted

spacing) blocked at the tail end of the field are commonly used for row crops. Wide beds (WB) with ~ 130 cm furrow spacing have also been introduced to improve crop performance (Hassan et al., 2005; Akbar et al., 2010). However, lack of knowledge and poor decision support system generally causes suboptimal irrigation management thus leading to poor irrigation performance on farms.

Irrigation management and field design improvement have been shown in many studies to significantly optimise irrigation performance (Kalwij, 1997; Raine et al., 1998; Dalton et al., 2001; Gillies and Smith, 2005). But there have been few attempts to optimise the furrow irrigation performance with improved irrigation management in the Indus Basin. Therefore, this research was aimed to evaluate the existing irrigation management of raised bed system on farm and to identify strategies for improving its irrigation performance.

Materials and Methods

Site descriptions and treatments

The study site was in northwest Pakistan, located in the Mardan district of Khyber Pakhtunkhwa province. Mardan lies in a semi-arid zone and receives a mean seasonal rainfall of 250mm in summer (April-September) and 300mm during winter (October-March). The mean maximum and minimum monthly temperature ranges from 27-30°C during June and decreases to 5-8°C during January respectively. The soil is sandy clay loam, classified as fine Usteric Camborthid, a greyish brown (Shafiq et al., 2002).

Each site was farmer managed and the irrigation performance was evaluated twice during the summer season. The irrigation performance was assessed for two bed treatments: (i) NB (Figure 1a) and (ii) WB (Figure 1b), each of which had three replicates. Each NB replicate comprised of five furrows and four beds and each WB replicate had four furrows and three beds. The field lengths ranged from 86-90m and all fields had a slope of ~0.002mm^{-1}. The beds were installed on a shallow cultivated (~15cm) and then rotary hoed fields. The experimental site conditions are summarised in Table 1.

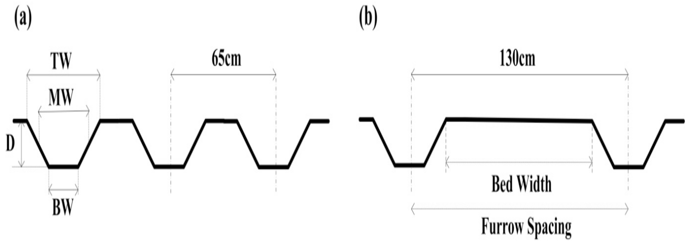

Figure 1: *Raised bed dimensions showing (a) NB: with furrow dimensions (TW: top width, MW: middle width, BW: bottom width and D: furrow depth; (b) WB: with bed size at Mardan*

Measurements

Furrow dimensions including top width (TW); middle width (MW); bottom width (BW) and furrow depth (D) were measured for all furrows at field head and middle sections prior to both irrigations at each site (Figure 1a). Antecedent soil moisture of bed shoulder and middle from a single bed of each treatment at plot head, middle and tail sections was determined gravimetrically at 15cm depth intervals to a depth of 60cm from undisturbed core samples dried at 105^{0}C for 48 hours. The soil moisture content was determined according to equation 1 (Lambe and Whitman, 1969):

$$\theta_m = M_w * M_d^{-1} *100$$

Where
θ_m = Soil moisture content on dry mass basis in %
M_w = Mass of water within the soil sample (g)
M_d = Dry mass of dry soil (g)

The soil bulk density ρ_b (g cm^{-3}) was calculated by dividing the dry soil weight (g) with the sample volume (98.214 cm^3) according to equation 2:

$$\rho_b = M_d * V_b^{-1}$$

Where
ρ_b = Bulk Density (g cm^{-3})

M_d = Mass of dry soil (g)
V_b = Bulk volume of soil sample (cm^3)

The volumetric soil moisture θ_v in (mm) per specific depth of soil layer was calculated by multiplying the gravimetric soil moisture with soil layer depth and its bulk density. The calculation were made as per following equation 3 (Dingman, 2002):

$$\theta_v = \theta_m * \rho_b * d$$

Where
θ_v = Volumetric soil moisture (cm)
d = depth of soil layer sampled (cm)

The required application depth (*Dreq*) was calculated as the difference between the antecedent volumetric moisture content and predetermined field capacity moisture levels of 23.5% (Shafiq et al., 2002; Hassan et al., 2005) for sandy clay loam soil in the region.

The total inflow from water course outlet (Q) was directed into five furrows of NB replicate or four furrowsof WB replicate per set. Furrow inflow rate was recorded at five minute intervals using a broad crested PVC pipe flume fitted to each furrow of a replicate. Water advance times at 18m, 36m, 54m, 72m and 90m length along each furrow were manually recorded using a stop watch. The time to irrigation cut-off (*Tco)* management was according to farmer's preference as per routine practice.

Irrigation performance evaluation

The furrow bed irrigation systems were evaluated using the WinSRFR 4.1.3 (Bautista et al., 2012). The WinSRFR integrates tools for irrigation system evaluation, irrigation system design and operational analysis. The WinSRFR model has been extensively used (Ali, 2011; González et al., 2011; Campo-Bescós et al., 2015; Roldán-Cañas et al., 2015) for evaluation and optimization of surface irrigation performance throughout the world. The WinSRFR is coded into four colours worlds (Bautista et al., 2009) with the names Event Analysis World (Irrigation event analysis and parameter estimation functions), Physical Design World (Design functions for optimizing the physical layout of a field), Operations Analysis World (Operations functions for optimizing irrigations) and Simulation World (simulation functions for testing and sensitivity analysis).

Field irrigation data and infrastructure details were entered into the model using the Event Analysis World for model as described by Bautista et al. (2009). The model calibration was based on a fair compatibility of the observed advance and recession curves with the simulated ones. The soil infiltration functions i.e. *a*, *b*, *c* and *k* parameters of the (Philip, 1969) equation were determined using the calibrated model for each irrigation event.

The calibrated model was used for evaluating the following irrigation efficiencies as per definition given in Bos (1985); Clemmens and Strelkoff (1999) and Bautista et al. (2012):

Application Efficiency (AE): It is the ratio of infiltrated depth contributing to irrigation target *(Dz)* to total irrigation depth applied *(Dapp)* or water received at the field inlet. When *Dz* is equal to minimum infiltration depth *(Dmin)* then it is called application efficiency of the minimum *(AE min)* and when *Dz* is equal to low quarter infiltration depth *(Dlq)* then it is called application efficiency of the low quarter *(AE lq)*.

Potential Application Efficiency (PAE): Attainable *AE* when inflow rate and time to cut-off are such that *Dlq* = *Dreq* (required irrigation depth) then it is called potential application efficiency of the low quarter *(PAE lq)* and when *Dmin* = *Dreq* then it is called potential application efficiency of the minimum *(PAE min)*.

Adequacy (AD): It is the ratio of *Dlq* to *Dreq* for adequacy based on low quarter *(AD lq)* and the ratio of *Dmin* to *Dreq* for adequacy based on minimum infiltration depth *(Admin)*.

Distribution uniformity (DU): It is the ratio of *Dlq* to *Dinf* (average depth of infiltrated water, infiltrated volume/area) for *DU lq* and the ratio of *Dmin* to *Dinf* for *DU min*.

Optimising irrigation efficiency with operation and field design options

The calibrated infiltration functions were used for evaluating different operation and field design scenarios using the Operation and Design World of the model. As in warabandi system the inflow rate per set is difficult to change due to system limitations. However, inflow rate per furrow can be changed by increasing or decreasing the number of furrows per set, as generally whole field width are not irrigated per single set. Thus the performance contours generated by WinSRFR were used for evaluating the impact of variable *Q*, *Tco*, field length and field width (number of furrows) on irrigation efficiencies *AE lq* and *PAE lq*.

Results

Existing irrigation management of raised bed systems

The average *Dreq* (0-60cm root zone) was ~60mm prior to both irrigation events on all sites (Figure 2). However, the surface soil was generally drier than at depth, for instance the *Dreq* in the 0-15cm depth was ~32% higher than the *Dreq* of the 15-60cm depth interval.

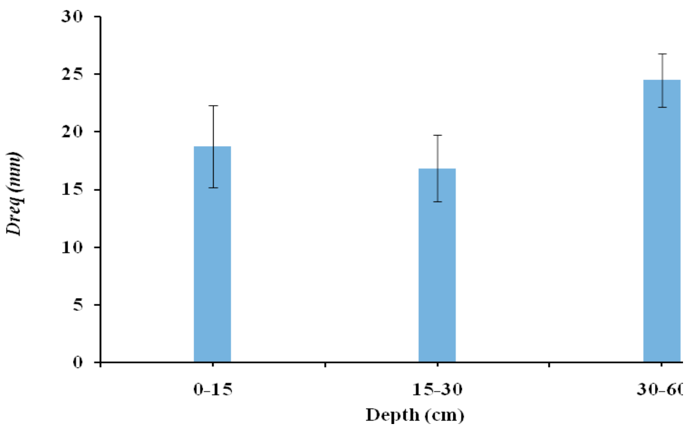

Figure 2: *Average required application depth (**Dreq**) in three soil layers (0-15 cm, 15- 30 cm and 30-60 cm) on three sites, measured prior to two irrigation events on a sandy clay loam at Mardan, northwest Pakistan (Vertical bars show SD)*

The WB furrows were significantly (*P=0.05*) wider (up to 35%) than NB (Figure 3) but the furrow depths were comparable between NB and WB. The average furrow top width on NB was smaller than the commonly available tractor tyre width (35cm) in the locality and greater on WB, indicating less risk of furrow side compaction on WB systems.

Inflow rate per set (Q) was higher for WB (14.8 lps) than NB (11.5 lps) as given in Table 2. Inflow rate per furrow was variable from farm to farm, and ranged from 1.5 to 4.9L.s^{-1}. The average Q per furrow was 2.3L s^{-1} on NB and 3.5L s^{-1} on WB. Average total inflow volume per single furrow of WB was 36% higher (range 5.4 to 9.75m^3) than NB (range 2.9 to 7.4m^3) during all irrigations evaluated. In contrast, total average volume of water applied per unit area was ~32% less on WB (60mm) than on NB (88 mm) due to the wider furrow spacing on the WB treatment.

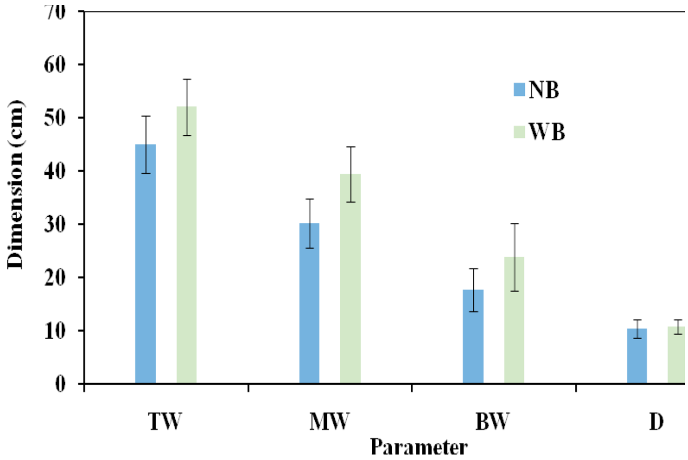

Figure 3: *Average furrow dimensions (TW = top width, MW = middle width, BW = bottom width and D = depth) measured prior to two irrigation events on three sites for narrow bed (NB) and wide bed (WB) at Mardan, northwest Pakistan (vertical bars show SD)*

Generally, the *Tco* was based on furrow filling time which was influenced by Q, water advance time to furrow tail end (*Ta*) and furrow dimensions. For instance, the diverging water advance curves (Figure 4) displayed a significantly (*P=0.05*) longer (~17%) *Ta* for NB than WB. Field observations indicated irrigation on wide beds often resulted in overtopping of the beds at the tail end. This phenomenon compelled the farmer to terminate the irrigation early, despite the centre of beds at the head end (~50% field length) of the furrows being dry.

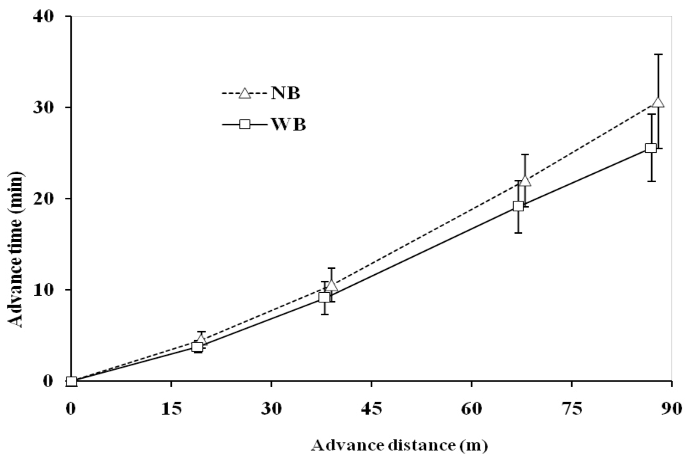

Figure 4: *Effect of bed size on average water advance rate along furrow length in three sites during two irrigations on a sandy clay loam at Mardan, northwest Pakistan (vertical bars show SD)*

Table 2: *Average irrigation operation (Q, Tco), field design (L, W, TW, BW and D) and irrigation efficiencies (AE lq, DU lq and AD lq) values measured during two irrigation events on three sites of sandy clay loam in northwest Pakistan (Standard Deviation in brackets)*

Treatment	Q* (lps)	Tco (min)	Field Dimensions (m)		Furrow dimensions (cm)			AE lq(%)	DU lq(%)	AD lq(%)
			L	W	TW	BW	D			
NB	11.5	36.5	89	3.3	45	17.7	10.3	71.3	70.3	100
	(3.1)	(2.7)	(2)	(0)	(6.4)	(2.9)	(1.4)	(15.7)	(7.4)	(40)
WB	14.8	33.7	89	5.2	52.2	23.8	10.8	87.3	79.5	90
	(5.7)	(1.5)	(2)	(0)	(8.7)	(11.1)	(1.2)	(18.7)	(3.4)	(30)

**Q = Inflow rate in litres per second per set of furrows; Tco = Time to irrigation cut-off; L = Field length; W = Field width; TW = Furrow top width; BW = Furrow bottom width; D= Furrow depth; AE lq = Application efficiency of low quarter; DU lq- Distribution uniformity of low quarter; AD lq – Adequacy of low quarter*

Existing irrigation performance of raised beds

The average *AE lq* was 71% on NB and 80% on WB (Table 2). The poor *AE lq* on NB indicated greater deep drainage losses and vice versa for WB. The *DU lq* was lower for NB (70%) than WB (80%). However, in the majority (>80%) of irrigation events more infiltration occurred at the tail end, while head reaches received less irrigation. Consequently, *DU lq* was adversely affected and the poor lateral infiltration with dry bed middle issue was exacerbated, especially at head reaches of WB.

Optimising irrigation efficiency with operation and field design options

For NB, if the current number of furrows irrigated per set are unchanged and *Q* is changed among 10 lps, 20 lps and 30 lps then a maximum *AE lq* of 92% and *DU lq* of 82% are achievable at given *Q* and *Tco* as demonstrated in Figure 5. This strategy indicated around 25%, 12% achievable improvement in *AE lq* and *DU lq* from its current values respectively.

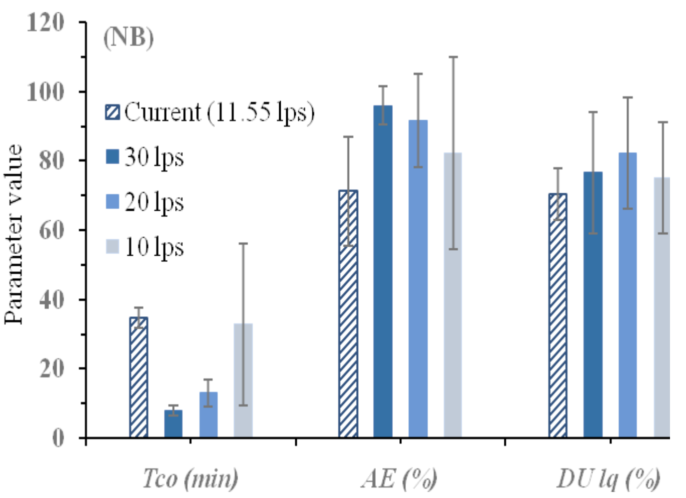

Figure 5: *Optimising irrigation efficiencies with changing inflow rate and time to cut-off for NB*

For WB, if the current number of furrows irrigated per set are unchanged and *Q* is changed among 10 lps, 20 lps and 30 lps then a maximum *AE lq* of 99% and *DU lq* of 81% are achievable at given *Q* and *Tco* in Figure 6. This strategy indicated around 12%, 2% achievable improvement in *AE lq* and *DU lq* from its current values respectively.

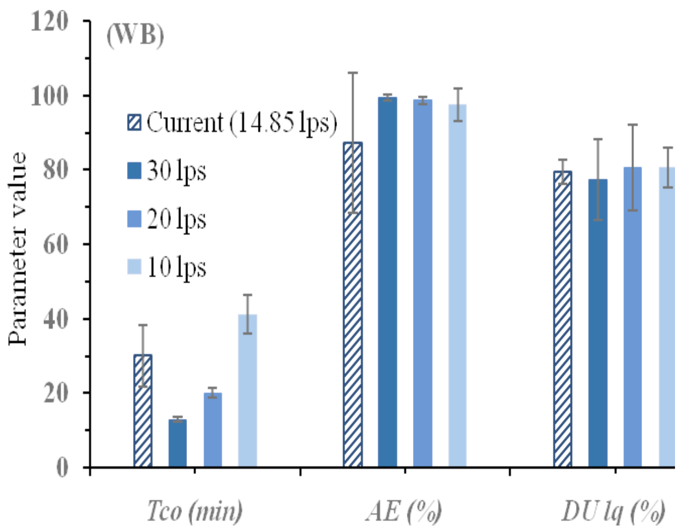

Figure 6: *Optimising irrigation efficiencies with changing inflow rate and time to cut-off for WB*

The results of optimizing potential application efficiency (*PAE*) for one irrigation event of *NB* by changing the field length, number of furrows and inflow rate per set indicated increased *PAE* tendency for short field length, reduced number of furrows and increased inflow rate as given in Figure 7.

For *WB*, optimizing potential application efficiency (*PAE*) for one irrigation event by changing the field length, number of furrows and inflow rate per set also indicated increased *PAE* tendency for short field length, less furrows and increased inflow rate as given in Figure 8.

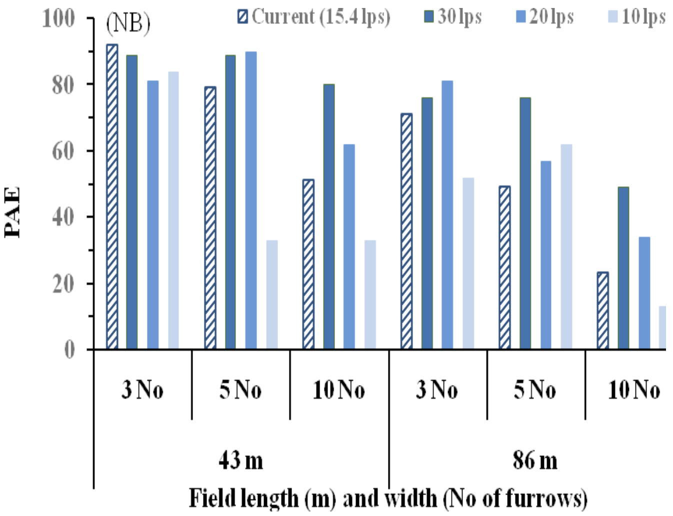

Figure 7: *Optimising potential application efficiency (PAE) with changing field length, number of furrows and inflow rate for NB*

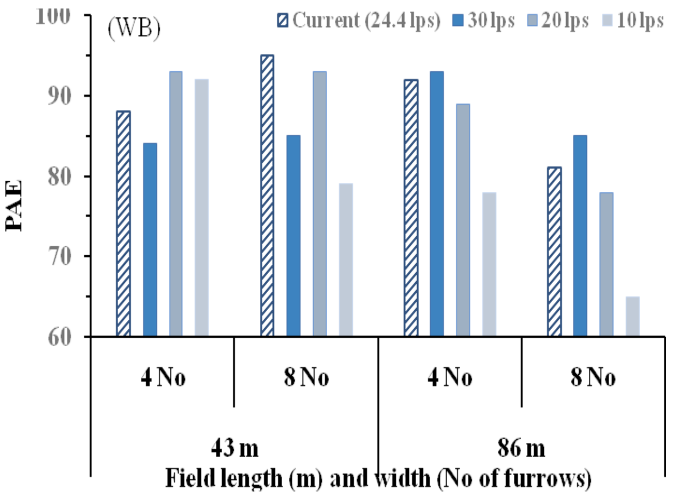

Figure 8: *Optimising potential application efficiency (PAE) with changing field length, number of furrows and inflow rate for WB*

Discussion

Irrigation management and performance interactions

The average required irrigation depth (*Dreq*) of ~60mm in 60cm root zone profile well represented the existing irrigation scheduling in this locality, as it also closely match the total evapo-transpiration values between irrigations during the summer season (Javaid and Usman, 2009). Field observations and analysis showed that changes caused by both treatments (NB and WB) significantly influenced the irrigation performance, which agree to the findings of Raine et al. (1997). Therefore, irrigation efficiencies were not optimised for the existing field conditions due to lack of knowledge and management guidelines.

The bed furrow systems with blocked ends significantly impacted on irrigation performance, as pointed out by Eldeiry et al. (2005), due to the variable water storage capacity per unit area. For instance, 32% larger irrigation volume was applied to NB compared with WB, which is consistent with the findings of Hassan et al. (2005). Consequently, less than adequate lateral infiltration can occur under the WB systems. The current study also revealed that irrigation applications were not sufficient to fulfil irrigation requirements, especially in the bed middle zone of WB according to visual observations. Thus to avoid negative impact on crops, smart irrigation practices, such as over topping the beds at crop germination and establishment stages are generally applied (Hassan et al., 2005; Akbar et al., 2007; Jin et al., 2007; Akbar et al., 2015).

Current irrigation management of measured furrow bed systems has been suboptimal leading to under or over irrigation. Excessive water application makes NB susceptible to excessive deep drainage losses as reported by Gill (1994). However, the current under-irrigation to WB causes inferior subbing as mentioned by Akbar et al. (2007). Importantly, this shows further potential to increase irrigation efficiency through better management options. Previous research also showed that the raised beds can save 50-60% of irrigation water (Gill et al., 2005)under cotton, wheat, and other crops compared with the prevailing flat basin or bay irrigation systems, if managed properly. Thus, optimised irrigation management can savewater by reducing deep drainage losses, which, in turn, can mitigate the risk of waterlogging and salinity (Yasin et al., 2002; Qureshi et al., 2008). All these facts necessitate the need for identification of strategies to improve the existing irrigation performance through better irrigation management.

Optimising irrigation efficiency with operation and field design options

This study illustrated greater potential for irrigation efficiency improvement of raised beds on small farms, which may also lead to increased water productivity. The key irrigation management factors revealed are inflow rate, time to cut-off and field length. Inflow rates are manageable by adjusting the number of furrows to be irrigated per set under the warabandi system. Importantly, optimising field length, width (number of furrows per set) and time to cut-off as per soil moisture deficit before irrigation has greater potential for achieving increased irrigation efficiency (up to 25% increase in *AE lq* in current study) for the available inflow rate in warabandi system. This strategy can also be beneficial especially, under WB to meet the deficit, which raises the prospect of saving labour by eliminating the need of manually dividing the field into much smaller segments and for mitigating inadequate subbing. The reduced deep drainage losses may be instrumental in mitigating the waterlogging and salinity issues mentioned by Qureshi et al. (2008).

Although the irrigation management strategies are generally site and event specific, subject to variations caused by field design, irrigation infrastructure, water infiltration capacity of soil, cultural practices and in-season changes, as mentioned by Gates and Clyma (1984). But the measurements, procedures, and graphic examples of irrigation performance variations with *Q*, *Tco,* furrow length and number of furrows per set can promote understanding of optimised irrigation performance with irrigation operation and field infrastructure changes. Moreover the applicability of these irrigation operation and field design tools is not universal, but application of the increased knowledge of irrigation performance interactions with field conditions is possible under the majority of available farm sizes (2-3 ha) and common flow rates (~ 20-30 ls^{-1}) from canals to field inlets in the Indus Basin.

Conclusions

The irrigation performance of raised beds is more sensitive to irrigation managementon small farms. The narrow beds are more susceptible to over-irrigation, which exacerbates drainage losses. In contrast, wide beds are more susceptible to under-irrigation, which may cause water stress to crop in bed middle. Optimising irrigation efficiency has been shown possible through changes in irrigation operation and field design, which may lead water saving by reducing deep drainage losses and can enhance distribution uniformity, thus can mitigate the poor lateral infiltration issue in wide beds. Simulation using WinSRFR provided a quantitative illustration of existing irrigation performance and the effectiveness in optimising irrigation efficiency through irrigation operation and field design strategies, which can be instrumental in reducing deep drainage losses, thus may reduce water logging and improve water productivity. The proposed irrigation efficiency optimisation strategies and the use of increased knowledge of measurements, evaluation procedures and graphical tools could improve decision support systems for improving the current irrigation performance with little infrastructure, machinery, or labour cost, which can be helpful for a wide range of soils and field layouts under wider environmental conditions of Indus Basin.

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Authorss Contribution

GA conducted the study and collected and analysed the data and contributed in developing this research paper as part of his PhD study. SR played a supervisory role and helped in providing the financial resources, finalising the experimental design, data analysis, presentation and reviewed the paper. ADM guided for using the field equipments, simulation mdelling and also reviewed the paper. GH helped in finalsing the data collection plan, supported in data anlysis and improving the presentation and QH supported in data collection, establishing field trials, data compilation and analysis.

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