Performance evaluation and optimization studies of border irrigation system for wheat in the Indian Punjab

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ABSTRACT

Surface irrigation methods are the most widely practiced worldwide for irrigation of row crops. The major problem with these methods is low irrigation efficiency, mainly due to poor design. In the Punjab, border irrigation is used to irrigate wheat crops grown over 90% of the cultivated area. The evaluation of existing border systems using a surface irrigation model showed that the irrigation conditions, comprising of inflow rate, border dimensions, and cut-off time, were diverse in tubewell and canal irrigated areas. The study also examined the feasibility of optimizing border dimensions taking into consideration the existing irrigation conditions for achieving more than 60% application efficiency as compared to the 30–40% achieved under present field conditions. In the case of a border length of 60 m, it was recommended to increase border width in the range of 10–45 m and 20–60 m for different flow rates of 10, 20 and 30 L/s in light and medium soils, respectively. For higher flow rates, a border length ranging from 120–150 m was found to be optimum. For a border length of 150 m, it was recommended to keep a border width ranging from 4–38 m and 8–65 m in light soils and medium soils, respectively, for flow rates of 10, 20, 30 and 60 L/s. Optimizing border dimensions is a practical way to achieve efficient and judicious use of water resources.

Keywords: border irrigation, water management, surface irrigation, application efficiency, Indian Punjab

INTRODUCTION

The development of the Indian economy is based on agriculture, as this is the main occupation of the people, especially in rural areas. Since independence, many efforts have been made to increase agricultural production to meet the requirements of an ever-increasing population in the country. Land and water are the major resources of agricultural production. About 80–85% of total water resources are utilized for agriculture. (Kaur, 2011). Identifying the various components of water losses and what improvements can be made is fundamental to the effective use of this resource in agricultural areas (Ting et al., 2009). The significance of irrigation efficiency in agricultural water management has already been emphasized in many earlier studies (Valipour and Montazar 2012a, 2012b, 2012c; Valipour et al., 2013; Valipour et al., 2013a, 2013b; Mahdizadeh Khasraghi et al., 2015).

The state of Punjab is located in the northwest of India. It extends from 29.30° N to 32.32° N and 73.55° E to 76.50° E. The total area of Punjab is 5.036 million ha and net irrigated area is 4.14 million ha (82.2%) out of which 2.981 million ha (72.0%) is irrigated by tube wells and the remaining area of 1.160 million ha (28.0%) is irrigated by canals (Brar, 2016). The region is popularly known as the food bowl of India as it contributes 41.5% of wheat and 24.2% of rice to the national pool. In this region, surface irrigation covers about 90% of the total irrigated land. The border method is widely adopted to irrigate field crops like wheat, as it does not need a lot of energy or special equipment. However, the poor design, implementation, and management of surface irrigation systems is generally responsible for inefficient irrigation that seldom exceeds inflow rate. Soil type is generally fixed for a given location, yet to achieve high irrigation performance system variables such as time of cut-off (t_{co}), border length (L) and border width (W) for a given depth of water can be altered. 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. Although the design of border irrigation systems is quite complicated and needs intensive engineering calculations (Khanjani and Barani, 1999), in recent times many models have been based on ‘rule of thumb’ of rough empirical guidelines, and approximations. Jurriens et al. (2001) has enabled engineers to systematically improve irrigation system design and operation. Some examples of irrigation models that have been used for design and evaluation purposes include SRFR (Strelkoff et al., 1977); SIRMOD (Walker, 1987) and SURDEV (Jurriens et al., 2001). In Punjab conditions, the border length is fixed for the cropping season and the width can be varied according to crop water requirements. The optimal application efficiency (*Ea*) and minimum runoff fraction (*Rf*) under different field conditions and available flow rate (*Qo*) may be achieved by varying the time of cut-off (t_{co}) and border width (*B*) for a given depth of water application (*Dreq*).

In the region, border length and width range between 50–300 m and 4–60 m, respectively, flow rate ranges from 5 L/s to 100 L/s and cut-off time varies between 100 and 600 min. Therefore, the present study was planned to (i) analyse the performance of the existing border sizes (ii) optimize the border dimensions and cut-off time under different flow conditions, and (iii) target minimum application depth to achieve maximize application efficiency in Punjab State, India.

MATERIALS AND METHODS

Study sites

Two villages, namely Ramgarh in Patiala District (tubewell irrigated) located 30° 32′ N and 76° 42.32′ E, and village Bargari (canal command area) located 30° 31.26′ N and 74° 57.08′ E

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in Faridkot District, were selected. The villages were chosen according to water supply conditions for irrigation. The location of the villages is shown in Fig. 1.

There was a typical crop rotation of winter wheat (Nov–April) and summer rice (Jun–Oct) in the selected fields. Winter wheat commonly needs 4 to 5 irrigations during its growing season as the precipitation is not sufficient to meet the crop water demand. The depth of each irrigation was kept as 75 mm which is recommended by the Punjab Agricultural University (Anonymous, 2016) and is widely practiced by the farmers.

Field survey

The participatory rural appraisal (PRA) survey was conducted to identify the gaps in water management practices. The information on land holdings; soil type; topography; field size; source of irrigation; mode of water conveyance; cropping pattern; land preparation sequence; flow regulation and irrigation scheduling were part of the PRA. Soil samples were also taken from 0–15 cm depth and analysed using hydrometric method. The volumetric method was used to determine the discharge of the water source. The information on potential problems in irrigation was also collected by interviewing farmers and through written questionnaires as follows:

- Do you do anything for land levelling before sowing?
- Has the availability of irrigation water remained the same in the past 10 years?
- How do you select the method of water application?
- Are you fully satisfied with your method of irrigation?
- Do you think it is necessary to have complete knowledge of method of irrigation, irrigation water measurement and water conveyance?
- Are you sure that you are using irrigation water efficiently?
- How do you ensure that desired amount of water has been applied?
- Do you have an adequate amount of irrigation water available?
- Is the water available when you need it?
- Do irrigation officials interact with the farmers regularly?

SURDEV software

SURDEV (Jurriens et al., 2001) is a user-friendly computer package for the design, operation and evaluation of surface irrigation systems. The package enables the user to simulate many of the problems involved in the practice of surface irrigation. In addition to simulations, SURDEV performs calculations of the optimal flow rates, field lengths, and cut-off times necessary in surface irrigation situations. The volume balance model (Lewis and Milne, 1938; Hall, 1956; Philip and Farrell, 1964; Wilke and Smerdon, 1965; Hart et al., 1980; Levien and Souza, 1987; Walker and Skogerboe, 1987) consists of a spatially and temporally lumped form of the continuity equation and is applied primarily to the advanced phase.

In this study, soil infiltration properties were based on one-dimensional modified Kostiakov equation which assumes that the advance time obeys a power law and infiltration is assumed to be a function of time only. The relationships between cumulative infiltrated depth (*Di*) and instantaneous infiltration rate (*I*) with the elapsed time (*T*) are given by Eqs 1 and 2, respectively:

$$D_i = kT^A + f_o T \tag{1}$$

$$I = kAT^{A-1} + f_o \tag{2}$$

The observed field data was used in SURDEV software to evaluate various parameters, viz., application efficiency, storage efficiency, percolation and runoff in existing border sizes. The input parameters included the soil type, required amount of application (*Dreq*), Manning's roughness coefficient (*n*), the field slope (*So*), the intake family (*k*, *A* and *fo*; modified SCS intake families for the Kostiakov equations). The value of *Dreq* depends on the climatic conditions, crop to be sown, soil conditions and the irrigation scheduling strategy, and in the case of a wheat crop grown under Punjab conditions *Dreq* was taken as 75 mm. Manning's roughness coefficient (*n*) is a measure of the resistance effects that flow might encounter as it moves down the border, which is in fact a representation, in somewhat lumped form, of the effects of the roughness of the physical boundaries of the

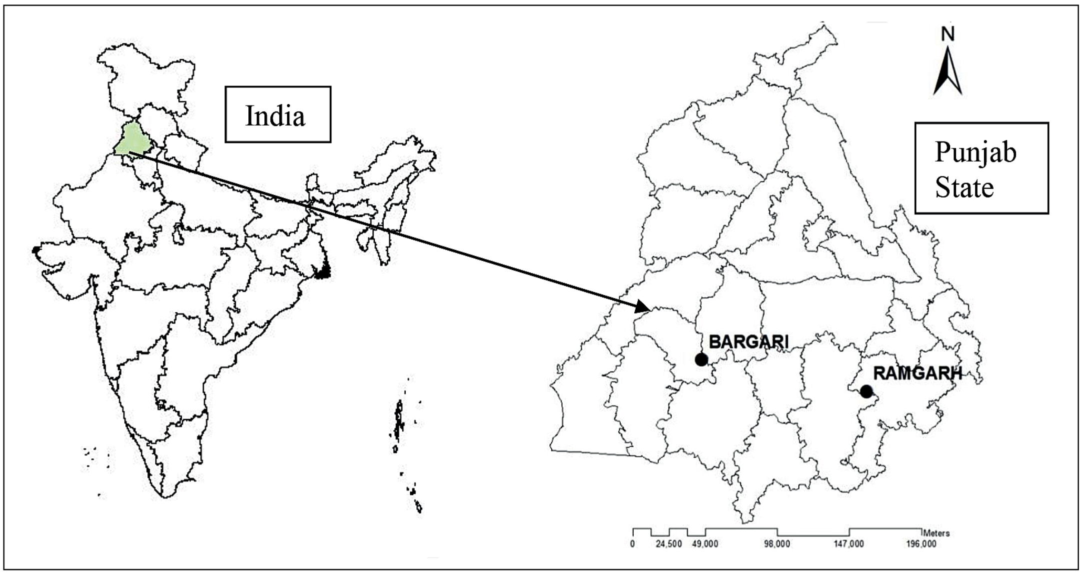

Figure 1
Map showing the locations of villages

flow and cultivation practices. For small-grained crops under different soils, this value is considered as 0.1 (Jurriens et al., 2001). Based on the field experience, the slopes of 0.5% and 0.3% were considered in sandy and loamy soils, respectively (Anonymous, 2017). Average values of other properties, such as bulk density, saturated hydraulic conductivity, were considered from literature (Singh et al., 2009). The infiltration parameters, which are primarily soil dependent, have been selected on the basis of the modified SCS intake families (Walker, 1987) for the modified Kostiakov equations and were taken as 1.0 and 0.6 in sandy soils and loamy soils, respectively. Other parameters (Table 1) were considered for the modified Kostiakov equation.

Optimization of border design

The parameters (border length, slope, soil and inflow rate, irrigation depth) are generally fixed for a given location; however, to achieve high application and storage efficiency one can alter border width and cut-off time (t_{co}). The cut-off time and border width were optimized using SURDEV for border lengths of 60 m, 120 m and 150 m; flow rates of 10, 20, 30, and 60 L/s (which are predominant in field conditions of the State) and two different soil types. The purpose of optimization of these two parameters was to achieve an application efficiency (*Ea*) of more than 60% and the storage efficiency (*Er*) such that the minimum infiltrated water depth at the end of the border equals the minimum required water depth (*Dreq*) and least surface runoff fraction and deep percolation losses, respectively. The sensitivity analysis of border width and cut-off time was done to evaluate which factor was more predominant in the design of a border irrigation system. The sensitivity analysis was done by varying the width by one unit and keeping all the other parameters fixed, and subsequently by varying cut-off time while retaining all other parameters.

RESULTS AND DISCUSSION

Field evaluation

The results of the field survey and soil sampling are presented in Table 2. In Ramgarh village, the discharge at the farmer's field varied from 7.4 to 22.3 L/s, whereas in Bargari village the range was from 50 to 67.8 L/s. There was considerable variation in the plot sizes adopted by farmers in both the villages. A length:width ratio of 10–11 in the canal-irrigated area and of 6–7 in the tubewell-irrigated area was prevalent. In Bargari village, the length (L) of the plot size varied from 62–225 m and width (B) varied from 9.2–20 m for the wheat season, whereas in Ramgarh village, the plot length and width ranged between 25–97 m and 6.3–15 m, respectively.

There was variability in sand, silt and clay percentages in the selected villages. In Bargari village, the average variation ranged from 45–61% for sand, 23–41% for silt and 12–18 % for clay, with 50% farmers having predominantly loam soils, 40% sandy loam and 10% other soil types. In Ramgarh village, this ranges from 70–81 % for sand, 13–23% for silt and 8–14 % for clay, with 50% of farmers having sandy loam, 39% loamy sand and 2% loam soil (Table 2).

TABLE 1
Modified Kostiakov infiltration parameters for different intake families

Intake family	*k* (m/min)	*A*	f_0 (m/min)	Soil type
0.6	0.00320	0.529	0.000136	Loam (medium soils)
1.0	0.00332	0.598	0.00212	Sand (light soils)

TABLE 2
Field parameters at different sites

Sr. No.	Farmer ID	Discharge (L/s)	Dimension *L* x *B** (m)	Soil type
Bargari Village				
1	BF01	58.0	62 × 10.5	Loam
2	BF02	50.1	165 × 15.0	Loam
3	BF03	57.5	126 × 9.2	Sandy loam
4	BF04	66.3	186 × 16.0	Loam
5	BF05	50.0	127.5 × 12.3	Loam
6	BF06	67.8	100 × 30.0	Sandy loam
7	BF07	57.6	180 × 18.0	Loam
Ramgarh Village				
1	RF01	21.4	71.4 × 7.4	Loamy sand
2	RF02	7.4	25.0 × 6.3	Loamy sand
3	RF03	8.8	150 × 8.0	Loamy sand
4	RF04	21.2	51.2 × 7.8	Loamy sand
5	RF05	36.5	51.4 × 8.2	Sandy loam
6	RF06	12.8	60.0 × 12.0	Sandy loam
7	RF07	20.1	55.7 × 7.8	Loamy sand
8	RF08	22.3	55.7 × 8.5	Sandy loam

**L* = *length and B* = *breadth*

TABLE 3
Evaluation of border system under existing field conditions

Village	Ramgarh (Tube-well irrigated)		Bargari (Canal irrigated)	
Name of farmer	RF03	RF04	BF02	BF03
Field parameters				
Border length (m)	150	60	165	126
Border width (m)	8	20	15	9
Flow rate (L/s)	8.8	21.2	50.1	57.5
Cut-off time (min)	480	100	45	120
Output parameters				
Minimum infiltrated depth (mm)	133	51	35	60
Application efficiency (%)	36	51	70	18
Storage efficiency (%)	100	72	51	87
Runoff ratio	29	49	30	82
Average applied depth (mm)	149	54	38	65
Over-irrigation depth (mm)	74	0	0	0
Under-irrigation depth (mm)	0	21	37	10
Over-irrigation length (m)	150	0	0	0

The simulation results of border systems under existing field conditions are presented in Table 3. The poor performance of existing irrigation systems is mainly dependent on the combination of present inflow rate, mismatched border dimensions and cut-off time. In the case of the tubewell-irrigated region, where the discharge is less,

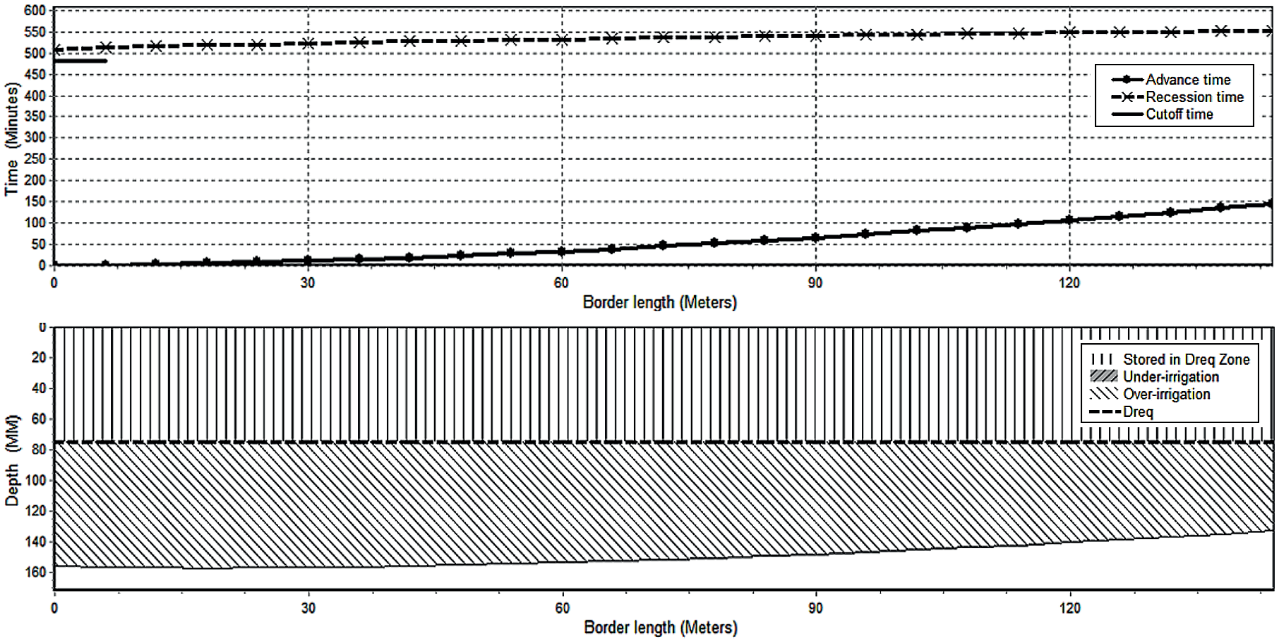

Figure 2

Advance curve and recession curve at farmer's field (RF03)

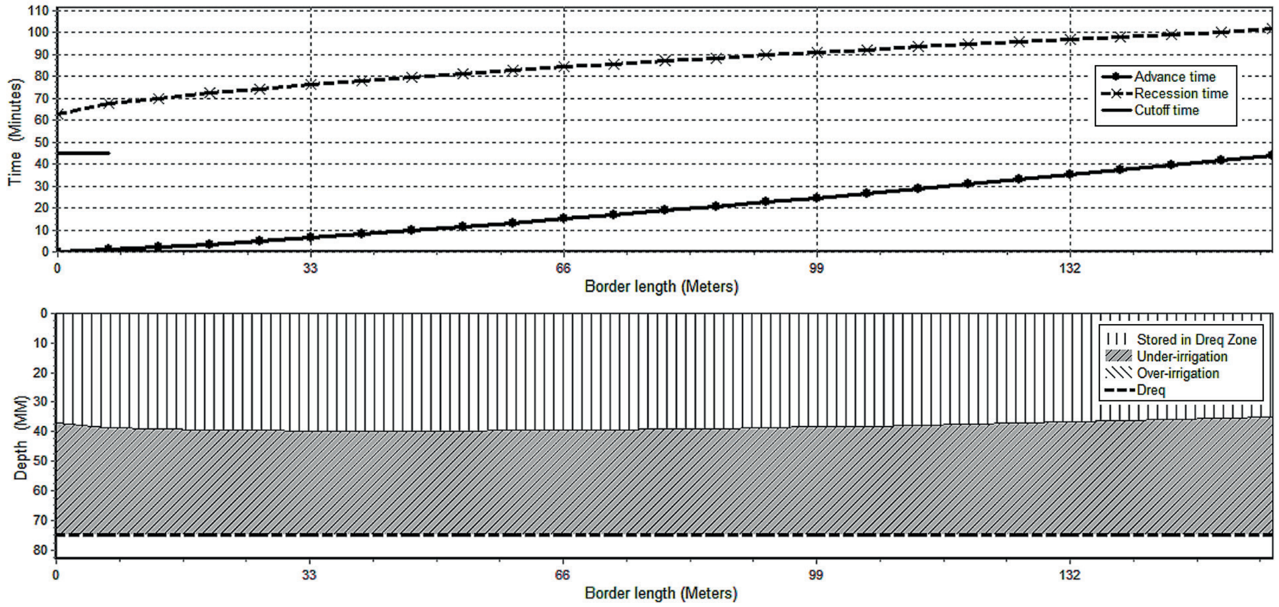

Figure 3

Advance curve and recession curve at farmer's field (BF 02)

farmers often keep the tubewell on for 7–8 h for filling of one plot which results in over-irrigation of the entire length of field, as shown in Fig. 2. The water infiltration distribution profiles are non-uniform along the length of borders. Although the farmer is able to attain more than 100% storage efficiency with average irrigation depth of 149 mm, against a required depth of 75 mm, this results in a low application efficiency of 36%. However, in the case of a tubewell-irrigated area with medium discharge and cut-off time of 1.5–2 h, better application efficiency was achieved but the storage efficiency was less than required (Table 3).

In the case of the canal-irrigated area, the farmer gets their water supply at their turn, depending upon the cropped area. Although the discharge is high, the farmer has limited awareness about the relevant plot size and appropriate cut-off time. Table 3 presents two cases of canal irrigation with application efficiency varying between 18 and 70%. In both cases under-irrigation at depths of 37 mm and 10 mm were observed (Fig. 3), relative to the required depth of 75 mm, due to short cut-off times and variation in plot sizes.

Evaluation of border optimization of border design

The design of a border irrigation system considers the flow to be non-linear. Therefore, the border width does not vary proportionally with flow rate and border length. The range of border width, cut-off time, deep percolation ratio and runoff fraction for different border lengths, flow rates, and soil types is presented in Tables 4 and 5, respectively. The range was obtained to achieve an application efficiency of more than 60% and required depth of irrigation throughout the border length. The optimum design parameters are highlighted in grey for different border lengths and flow rate in Tables 4 and 5.

For a given border length, the border width was found to be more affected by soil type, with a minimum in light and maximum in medium soils, irrespective of the flow rate. A comparison of existing farm conditions (Table 2) with simulated results (Table 3) shows that performance efficiency can be improved by adopting recommended cut-off time and width. Considering the case of farmer RF03, with length 150 m; width 8 m; flow rate 8.8 L/s; and t_{co} of 480 min yielded an *Ea* of 36% which can be improved to 64% by decreasing width to 6 m and cut-off time to 176 min. Similarly, for Farmer BF03 (Table 2), the application efficiency can be enhanced from 18% to 66% by increasing the width from 9 m to 35 m.

In the case of small plot size, as the flow rate increases, the application efficiency decreases and surface runoff increases. It is suggested that for a border length of 60 m, border width should be kept in the range of 10–45 m and 20–60 m for flow rates of 10, 20 and 30 L/s in sandy and loamy soils, respectively. Therefore, at higher flow rates border length

TABLE 4
Evaluation of border irrigation parameters in light soils for 75 mm depth of irrigation

Flow rate (L/s)	Width (m)	Cut-off time (min)	Application efficiency (%)	Deep percolation ratio (%)	Runoff (%)
Length = 60 m					
10	10	122–124	63	9–10	29–30
10	14	157–176	67	20–25	13–15
10	16	187–201	64	28–32	8–9
20	20	119–126	62	8–10	29–30
20	24	135–151	66	13–18	20–22
20	28	157–60	67	20–25	13–15
20	30	170–189	66	24–29	10–12
30	35	133–146	65	13–15	21–23
30	40	149–168	67	16–18	15–23
30	45	172–189	66	10–12	25–29
Length = 120 m					
20	10	119–126	63	10–12	27–28
20	15	174–189	64	26–30	9–10
30	15	119–126	63	10–12	27–28
30	20	151–168	66	12–20	14–16
30	25	204–210	61	33–34	6–7
60	30	119–126	63	10–12	27–28
60	35	133–147	66	15–19	20–22
60	48	191–201	63	30–32	7–8
Length = 150 m					
10	4	118–125	63	26–27	11–13
10	6	176–186	64	27–30	9–10
20	7	109–110	61	32–33	8–9
20	10	142–157	66	18–22	16–18
20	13	198–204	62	32–33	6–7
30	11	112–115	61	9–10	30–31
30	15	142–157	66	18–22	16–18
30	20	206–210	61	34–35	6–7
60	21	108–110	61	8–9	32–33
60	35	169–183	65	26–29	9–10
60	40	206–210	61	34–35	5–6

TABLE 5
Evaluation of border irrigation parameters in medium soils for 75 mm depth of irrigation

Flow rate (L/s)	Width (m)	Cut-off time (min)	Application efficiency (%)	Deep percolation ratio (%)	Runoff
Length = 60 m					
10	20	233–252	64	11–14	25–26
10	24	270–302	67	17–22	16–18
10	32	396–403	61	34–35	5–6
20	34	211	60	33	7
20	40	233–251	64	11–14	25–26
20	50	282–315	67	19–24	14–16
30	50	209	60	7	34
30	60	233–252	64	11–14	25–26
Length = 120 m					
10	10	232–252	65	12–16	23–25
10	16	403	60	36	5
20	18	216–226	62	9–11	28–29
20	22	251–276	66	16–19	19–21
20	32	403	60	36	5
30	25	207	60	8	32
30	35	265–294	66	18–22	16–18
30	40	307–335	65	24–28	11–12
60	50	207	60	8	32
60	55	219–230	63	10–12	27–28
60	60	232–252	65	12–16	23–25
Length = 150 m					
10	8	232–252	65	13–16	22–24
10	12	365–378	62	32–33	6–7
20	18	256–283	66	17–21	17–19
20	25	390	60	35	5
30	20	205–210	61	8–9	31–32
30	25	240–262	65	14–18	21–23
30	38	399	60	35	5
60	40	205–210	61	8–9	31–32
60	55	261–288	66	18–22	16–19
60	75	390	60	35	5

greater than 120 m should be adopted. For higher flow rates, a border length ranging from 120–150 m is found to be optimum. In the case of a fixed border length of 150 m, it is recommended to keep border width ranging from 4–40 m and 8–75 m in light soils and medium soils, respectively, for different flow rates of 10, 20, 30 and 60 L/s (Table 5). In case the flow rate increases from 10 L/s to 20 L/s, the width should also be doubled for different border lengths.

The cut-off time was largely affected by soil type and it is recommended that it vary between 119–210 min and 209–403 min in sandy and loam soils, respectively, for different flow rates and border lengths. Also, the allowable cut-off time ranges within 10–12% of the optimum cut-off time in the case of light soils and within 8–10% in medium soils, for optimum border width and different border lengths.

In light soils having a length of 150 m, if flow rate is known, the optimum application efficiency can be achieved by keeping the width at numerically half of the flow rate value, whereas in medium soils, this value was numerically equal to flow rate. At higher border lengths, cut-off time is be numerically equal to flow rate.

The sensitivity analysis showed that the application efficiency was sensitive to border width at low discharges and the decrease was more evident for longer borders. Also, the variation in efficiency was more prominent in light soils as compared to medium soils. It was also observed that at higher border lengths, cut-off time was insensitive to different flow rates and border widths.

CONCLUSIONS AND RECOMMENDATIONS

The groundwater depletion in Punjab State is at critical levels and the government is introducing many initiatives to address this problem. A practical and water-saving irrigation system is urgently required to relieve the lack of water resources in northern India. For this purpose, the potential of improving border irrigation performance through border dimension optimization was evaluated using a simulation model. Field studies indicate poor performance of current irrigation systems due to mismatched irrigation system conditions, for example, supply discharge, border dimensions, and relatively long cut-off distances. In this study, the effect of changes in border width and cut-off time for a desired depth of application and application efficiency of more than 60% under existing field conditions (flow rate, border length, slope and soil conditions) was evaluated. The simulated design shows that it is possible to select a suitable combination of the border system's parameters (border length, inflow rate, and cut-off time) to obtain an application efficiency of more than 60% compared to the existing efficiency of 30–40%. For efficient irrigation when the border width increases, the border length should be shortened. The coarser the soil, the shorter the field and the steeper the field slope, the more pronounced are the variations of the performance indices versus changes in inflow rate, border length and cut-off time. The results present a broad guideline for improving existing on-farm irrigation systems for better management of the scarce resources of agricultural production. However, this does not consider spatial and temporal variability in the parameters. Taking into account the case study area of the Punjab region, where wheat is grown over an area of 3 600 000 hectare having an average irrigation requirement of 400 mm. Optimizing border dimensions can save approximately 12 billion m^3/yr water for this wheat crop. Thus, it is sensible to persuade farmers to establish standard border dimensions for water saving farming practices in Punjab.

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