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WATER FRONT ADVANCE UNDER VARIABLE BORDER WIDTH AND INITIAL SOIL MOISTURE CONTENTS UNDER WHEAT (*Triticum aestuivium* L.) CROP – I: HYDRAULICS AND IRRIGATION EFFICIENCIES

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Abstract. Border irrigation experiments were conducted on wheat (*Triticum aestivum* L.) crop at Water Technology Centre, Indian Agricultural Research Institute (IARI) New Delhi in winter season (October-April) of 2013-2014 to study the border hydraulics (cutoff ratio, border width and stream discharge), irrigation efficiencies, grain and biomass yields for 4 border sizes (2, 3, 4 and 5 m widths) to economize the water use. Optimizing the border width under varying soil moisture contents prior to irrigation was attempted. The border of length 25 m required 30.2 minutes (min) to 78.1 min for irrigation for a fixed cutoff length of 15 m. The water front advance time up to cutoff length was 10 min and 27.3 min for border widths varying from 2 to 5 m; respectively corresponding to the selected stream discharge of 1.5 l/s. The water front advance time was inversely proportional to the initial soil moisture contents. The travel time to cutoff point of 15 m for three soil moisture contents namely θ1:14.2, θ2:16.5 and θ3:17.2%; varied from 10.0-11.7 min for the border size (width) of 2.0 m, 14.0-15.6 min for the border size of 3 m; 20.0-23.4 min for the border size of 4 m whereas, it took 24.5-27.3 min for 5 m border size. The best border size was identified as 4 m without any yield penalty. The effect of the stream discharge was not pronounced based on yields. Due to uniform cutoff ratio there was no significant difference in the amount of water use. Hence, the border size of 4 m was rated the best.

Keywords: *border irrigation, cutoff length, hydraulics, irrigation efficiency, wheat crop.*

Introduction

Water is one of the most important commodities for sustaining life. It is likely to become scarce in the coming future due to its increasing demands by the rapidly increasing population and competition from the industrial and domestic sectors as a result of rapid growth and economic expansion in many countries of the world (FAO, 2012). Physical and economic scarcity of water across different regions in the world as well as within nations has forced water resources scientist to critically analyze different options for managing water. Irrigation is an engine of agricultural growth all over the world (FAO, 2016). As water is becoming increasingly scarce due to growing demand for domestic as well as industrial purposes and other sectors, the development of water saving irrigation technologies are required. To obtain higher irrigation efficiencies application of comparatively less irrigation input than the traditional irrigation method is on the anvil.

India has the highest area under irrigation which is almost one fifth of the world's gross irrigated area (Postel, 1999). India's irrigated agriculture sector has been pivotal to India's economic development and poverty alleviation. In order to increase the area under irrigation, efforts are needed to increase irrigation efficiency on individual farms, which will save considerable amount of precious water resource. A study by the International Water Management Institute (IWMI) showed that around 50% of the increase in demand for water by the year 2025 can be met by increasing the effectiveness of irrigation. Recognizing the importance of sustainable water use efficiency in agriculture, several water management strategies (like introduction of modern methods of irrigation, scheduling, deficit irrigation, regulated deficit, water pricing, slow saturation of root zone, sub-irrigation, water user's association, turnover system etc.) have been introduced since the late seventies to improving the water use efficiency especially in the use of surface irrigation water in India (Seign, 1987; Sirsath *et al.*, 2009; Valipore, 2013).

Border-check method of irrigation is highly efficient method of surface irrigation, but these are usually designed and operated much below their potential level. The relevance of water application variability in irrigated agriculture has long been recognized. Scarcity of field scale information on the effects of water application uniformity and soil variability is a serious limitation to optimal design and management of surface irrigation systems (Bucks, Hunsaker, 1987). Three factors which can affect irrigation uniformity in a level basin were identified as: variations in opportunity time, surface retention of water and infiltration properties (Clemmens, 1988). Low efficiencies obtained in border, furrow and check basin irrigation are due to inadequate land levelling and uncontrolled water application (Khanna, Malano 2006).

Wheat (*Triticum aestivum L.*) crop is one of the most important staple food grains of human race. India produced 94.88 million tonnes of wheat during the year 2011-2012 which is about 13.53 percent of world's total production. Surface irrigation is, undoubtedly, the most popular method among the Indian farmers (Michael, 1978). Border method of irrigation popularly known as basin irrigation is one of the first irrigation techniques used (Clemmens, 1998). It has been described under several different names including check flooding and basin flooding (Israelson, 1950), level borders (Zimmerman, 1966; Merriam, 1968), check irrigation (Schwab *et al*., 1966), check basin irrigation (Michael, 1978) and border-check irrigation. Basin irrigation is defined as the application of water to an area typically levelled to around zero slope and surrounded by dykes or check banks to prevent runoff (Khanna, Malano, 2006). While various strategies introduced for improving the water use efficiency have been continuing but the net impact of these are not very impressive (Jensen, 2007; Ahmad *et al*., 2010; Chen *et al*., 2013; Chouhan *et al*., 2015). However, estimates indicate that with a 10 per cent increase in the existing water use efficiency, India could add 7 to 8 million ha to the irrigated area without utilizing additional water resources (Narayanamoorthy, 2002).

Border irrigation is a surface flooding method of water application under controlled conditions (Merrium, 1968; Elliot *et al*., 1983; Clemmens 1988; Clemmens, 1998). The field is divided into a series of long strips called borders that are separated by low ridges. The borders have a uniform downfield gradient and are level crosswise. Normally the direction of the strip is in the direction of the greatest slope, but some- times borders may be placed nearly on the contour. Water is turned onto the upper end of each strip and slowly flows towards the lower end in the form of a thin sheet **(**Kruse, 1978; Holzapfel *et al*., 1985; Holzapfel *et al*., 1986; Walker, Skogerboe, 1987). The knowledge of the hydraulic characteristics or flowing water is vital for designing an efficient water application system under border irrigation method. The fluid flow phenomenon of border irrigation is a case of Spatially Varied Unsteady Open Channel Flow with Decreasing Discharge (Reddy *et al*. 1981; Michael, 1993; Valipore, 2013). This flow phenomenon is affected by several variables that must be determined before proper design criteria for borders can be established (Yadav *et al*., 2002; Sun *et al*., 2010). The dominant variables are entrance stream size, infiltration, slope of the land surface, and hydraulic resistance. If a functional relationship is established between the dominant variables, border irrigation can be then described by water front advance, water storage and depletion, and tail water recession phases (Khanna *et al*., 2003; Neil *et al*. 2014). Looking to the general practice of growing wheat in this region with predominantly border irrigation, to achieve the high irrigation efficiency the present study aimed at optimizing the border width for a small on-farm stream having discharge 1.5 l/s under varying soil moisture contents prior to irrigation was attempted.

Materials and Methods

The study area

Field experiments were conducted at the Water Technology Centre's research farm during the winter season (October-April) of the cropping year 2013-2014. The rainfall that occurred on only two days (1st November 2015 and 1st February 2016), and daily reference evapotranspiration (ET_o) during the entire cropping season were recorded and plotted in figure 1 that shows almost constant ET_o and the least rainfall. The daily ET_o were estimated using Penman-Montieth equation (Allen *et al*., 1998). Different width of borders having sizes of 2.0, 3.0, 4.0 and 5.0 m; respectively, were prepared in triplicate. The land preparation was done using two disking from disk harrow and two runs of cultivators in criss-cross mode. A rotavator was used to break the clods and pulverize the soil. After that the ridges having 30 cm bottom width and 15 cm height were formed along 1 percent longitudinal slope from upstream (U/S) to downstream (D/S).

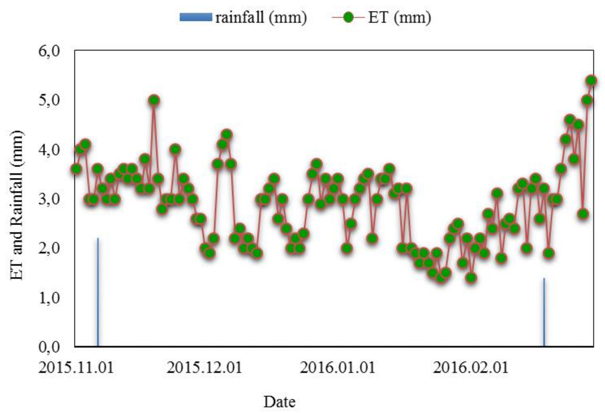

Fig. 1. Rainfall and evatranspiration (ET) variations during the field experimentation.

Details of the experimentation

Provision for water application and collection

An irrigation channel was created having trapezoidal cross section with depth as 15 cm, bottom width 5 cm and top width 15 cm on U/S. The water was brought from a pipe from the delivery of a small pump of 735.5 W. The stream discharge was calibrated at 1.5 l/s. A drainage channel at the D/S was also created with the similar specifications at the D/S section of the experimental plot to safely discharge any excess water coming out of the plot. The length of the borders was fixed at a maximum of 30 m.

Determination of the root zone soil moisture

The soil moistures were measured using gravimetric method. The data were recorded for the crop growth, development, morphometric parameters at each developmental stage. All the recommended normal agronomic practices were applied. Three runs were planned for study of the performance of border irrigation system and synchronized with three irrigations. The first run was made in the beginning of the sowing season and the moisture was used as pre-sowing irrigation. The second run was done at 29 days after sowing (DAS) of the crop that matched with crown root initiation (CRI) stage. The third and final run of the border irrigation matched with the peak developmental (PD) stages of the crop after 58 DAS depending upon the availability of water from the Farm

Operation and Maintenance Unit (FOSU) at IARI. The initial soil moisture contents in root zone prior to irrigation were measured gravimetrically.

Mathematical modeling of root zone soil moisture

Three trend lines namely: linear, logarithmic and exponential were fitted in three sets of data and the best fit curves were adjudged using R^2. Variation in the root zone soil moisture was fitted in the mathematical equations of three types as follows and the R^2 were worked out for comparisons:

linear model:

$$y = m \times x + C1, \quad (1)$$

exponential:

$$y = a \times e^{b}, \quad (2)$$

logarithmic:

$$y = a \times \ln(x) + C2, \quad (3)$$

where:

x – root zone depth;
y - dependent variable;
m - the slope of the line;
C1 - the intercept;
a, b and C2 - constants.

Measurement of discharge for determining different irrigation efficiencies

The amount of water received at the head of the border was determined using the time taken and the rate of discharge. For determining the storage efficiencies 10 soil samples from the entire plot were lifted and the moisture contents were determined gravimetrically in the Watershed Hydrology and Management Laboratory of the Water Technology Centre, IARI, New Delhi.

Estimation of different irrigation efficiencies under varying border lengths

Various irrigation efficiencies (%) namely; conveyance (ηc), application (ηa), distribution (ηd), storage (ηs); and overall project efficiency (ηp) during three runs have been worked out using the following methodology.

Water conveyance efficiency (ηc)

It indicates losses of water that occur while water is conveyed from source to the point of utilization. It is the ratio of water delivered to the plot to the total quantity delivered at the source (Panda, 2003):

$$\eta c = \frac{Wp}{Wr} \times 100, \quad (4)$$

where: ηc - water conveyance efficiency, %;
W_p - amount of water delivered to the plot;
W_r - amount of water delivered from the source.

Water application efficiency (ηa)

It is the ratio between the quantity of water stored in the root zone and the water delivered to the plot (Panda, 2003):

$$\eta a = \frac{Ws}{Wp} \times 100, \quad (5)$$

where: ηa - water application efficiency, %;
W_p - amount of water delivered to the plot;
W_s - amount of water stored in the root zone during irrigation.

Field water distribution efficiency (ηd)

It is a measure of uniformity of water distribution within the field.

$$\eta d = \left[1 - \frac{Y}{d}\right] \times 100, \quad (6)$$

where: ηd - water distribution efficiency, %;
Y - average numerical deviation in depth of water stored from an average depth of irrigation;
d - amount of water stored in the root zone during irrigation.

Water storage efficiency (ηs)

This concept gives an insight into how completely the required water has been stored in the root zone during irrigation. It is the ratio between water stored in the root zone and water needed in the root zone prior to irrigation.

$$\eta s = \frac{Ws}{Wn} \times 100 \quad (7)$$

where: ηs - water storage efficiency, %;
W_s - amount of water stored in the root zone during irrigation;
W_n - water needed in the root zone prior to irrigation.

Overall project efficiency (ηp)

It is the percentage of irrigation water stored in the root zone and available for crop consumptive use to the amount of water delivered at the source of supply (Panda, 2003). When the water is measured at farm head gate or water source, it is called project efficiency (ηp) and when measured at inlet to the field, it is called field irrigation efficiency.

$$(\eta p) = \eta c \times \eta a \times \eta d \times \eta s \quad (8)$$

RESULTS AND DISCUSSIONS

Different irrigation efficiencies under varying border lengths

Different irrigation efficiencies and overall project efficiency during three runs have been presented in Table 1. The average efficiencies in first run were 43.4, 38.1, 43.2, 46.7 and 33.8%. It reduced to 36.8, 34.5, 37.0, 41.1 and 19.6% after the second run and during the third run of the experiment these efficiencies again were found to be 33.7, 29.0, 43.1, 46.1 and 19.8 %; respectively. It was observed that application efficiency has resulted in overall poor project efficiency while the storage efficiency remained the highest throughout the experimental period.

Table 1. Different irrigation efficiencies under varying border lengths

Run	Size of the border, m	Irrigation efficiencies, %				
		ηc,	ηa,	ηd,	ηs	ηp
1	2	44.5	41.4	45.6	49.2	41.3
	3	44.0	38.8	44.7	48.6	37.1
	4	43.3	37.1	43.2	47.4	32.9
	5	41.7	35.0	39.1	41.6	23.7
Average		43.4	38.1	43.2	46.7	33.8
2	2	38.5	37.0	39.0	44.2	24.6
	3	37.4	36.4	38.4	41.7	21.8
	4	36.9	34.3	36.3	40.3	18.5
	5	34.2	30.2	34.1	38.1	13.4
Average		36.8	34.5	37.0	41.1	19.6
3	2	36.2	31.0	45.6	48.7	24.9
	3	35.5	30.6	44.3	47.4	22.8
	4	33.3	28.5	42.1	44.3	17.7
	5	29.8	25.8	40.5	44.1	13.7
Average		33.7	29.0	43.1	46.1	19.8

Advance curves of the 2 m wide border at different initial soil moisture contents

The border advanced curves with reference to the 2.0 m wide border when subjected to a small stream of 1.5 l/s has been plotted in figure 2. It could be observed from the figure 2 that advanced curve covered a distance of 20 m after 20 min. The cutoff time was 20 min after start of the experiment. It took nearly 30 min by the advance to reach the 30 m distance in almost all three soil moisture content conditions. The trend lines have also been fitted and it was noticed that they were concurrent meaning thereby that there was no significant difference in the elapsed time of advance at three soil moisture conditions in covering the desired length of the border.

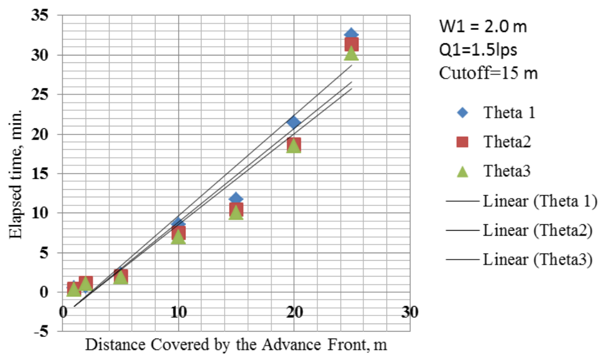

Fig. 2. Advance curves of the border W1 (2.0 m wide) with 1.5 l/s discharge (Q) and three initial soil moisture contents (θ1, θ2 and θ3).

Advance curves of the 3 m wide border at different initial soil moisture contents

The border advanced curves with reference to the 3.0 m wide border when subjected to a small stream of 1.5 l/s has been plotted in figure 3. It could be observed from the figure 2 that advanced curve covered a distance of 20 m after 22, 24 and 26 minutes for three initial soil moisture conditions i.e.; θ1:14.2, θ2:16.5 and θ3:17.2% respectively. The time taken by the advance in dry condition was more than the lower moisture. The cut off time was fixed at 20 minutes after start of the experiment. It took nearly 42, 44 and 46 minutes, respectively; for the advance to cover the border length (length of the border 30 m) in all three soil moisture content conditions. From the fitted trend lines it was noticed that they were almost concurrent; meaning thereby that there was no significant difference in the elapsed time of advance at three soil moisture conditions in covering the desired length of the border. It could be observed from the figure 3 that advanced curve could cover longer distance after 24 minutes. The cut off time was 15 minutes after start of the experiment.

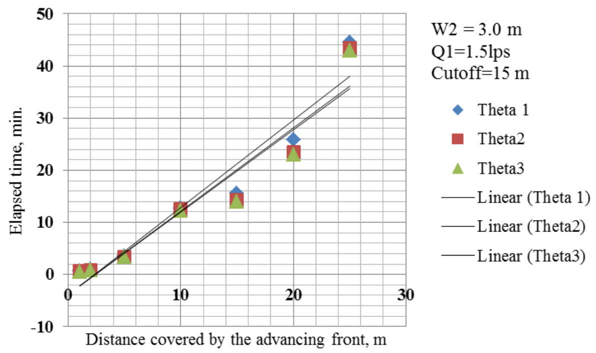

Fig. 3. Advance curves of the border in W2 (3.0 m wide) with 1.5 l/s discharge (Q) and three initial soil moisture contents (θ1, θ2 and θ3).

Advance curves of the 4 m wide border at different initial soil moisture contents

The border advanced curves with reference to the 4.0 m wide border when subjected to a small stream of 1.5 l/s has been plotted in figure 4. It could be observed from the figure that advanced curve could cover large distance after 25 minutes.

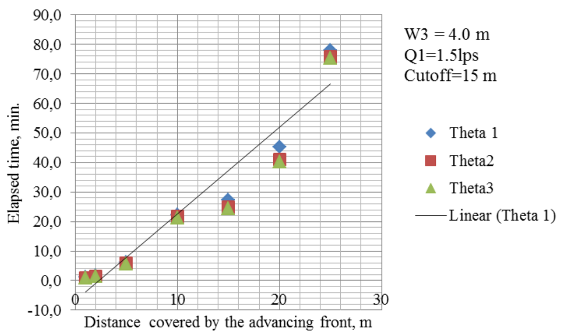

Fig. 4. Advance curves of the border in W3 (4.0 m wide) with 1.5 l/s discharge (Q) and soil moisture contents (θ1, θ2 and θ3).

The cutoff time was 50 min after start of the experiment. It could be observed from the figure 3 that advanced curve could cover 20 m distance after 40, 42 and 46 minutes for three initial soil moisture conditions. The time taken by the advance in dry condition being higher. The cutoff time was fixed at 20 min after start of the experiment. It took nearly 74, 76 and 78 min, respectively for the advance to cover the border length (length of the border 30 m) in all three soil moisture content conditions; respectively. The trend lines have also been fitted and it was noticed that they were concurrent meaning thereby that there was no significant difference in the elapsed time of advance at three soil moisture conditions in covering the desired length of the border.

Advance curves of the 5 m wide border at different initial soil moisture contents

The border advanced curves with reference to the 5.0 m wide border when subjected to a small stream of 1.5 l/s has been plotted in figure 5. It could be observed from the figure that advanced curve could cover large distance after 26 min. The cutoff time was 50 min after start of the experiment. It could be observed from the figure 4 that advanced curve could cover 20 m distance after 42, 44 and 46 min for three initial soil moisture conditions. The time taken by the advance in dry condition being higher. The cutoff time was fixed at 20 min after start of the experiment. It took nearly 76, 77 and 78 min respectively for the advance to cover the border length (length of the border 30 m) in all three soil moisture content conditions; respectively. The trend lines have also been fitted and it was noticed that they were concurrent meaning thereby that there was least significant difference in the elapsed time of advance at three soil moisture conditions in covering the desired length of the border.

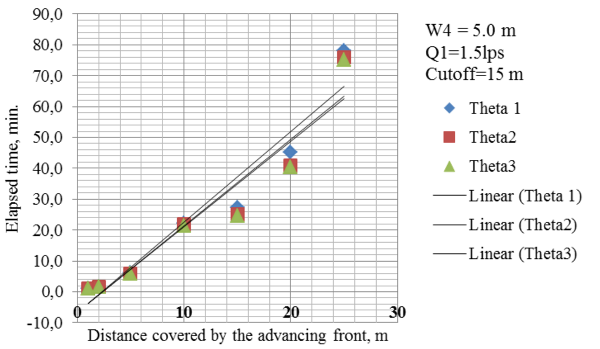

Fig. 5. Advance curves of the border in W4 (5.0 m wide) with 1.5 l/s discharge (Q) and soil moisture contents (θ1, θ2 and θ3).

However, the time for the advance to reach the end in 4.0 m wide border and 5.0 m wide border was at par with each other. The ET remained almost constant throughout the experimental period (Fig. 5) and it is expected that the drying of the soil might not have resulted into substantial changes in the flow behaviour of the borders.

Rainfall and ET (mm) variations during the field experimentation.

Small stream size might result into substantial amount of time and management at the apex level that the irrigation efficiencies were not very encouraging. The results of the present study are in accordance with the previously reported theories by (Strelkoff, Shatanawi 1985; El-Hakim *et al*., 1988; Strelkoff *et al*., 1996).

Profile soil moisture content prior to irrigation application

The soil moisture content θ1, θ2 and θ3 prior to irrigation has been presented in Table 2. Average profile soil moisture content prior to irrigation application in upper root zone layer (0-45 cm) during three replications were 19.6, 20.6 and 22.9 %; respectively. Average profile soil moisture content prior to irrigation application in middle root zone layer and (45-115 cm) during three replications were 14.4, 16.7 and 18.4 %; respectively. Average profile soil moisture content prior to irrigation application in bottom root zone layer (115-150 cm) during three replications were 10.8, 13.6 and 17.2%; respectively. This indicated a progressively reducing root zone soil moisture and partially unsaturated root zone prior to starting the irrigation. The figure 1 shows the rainfall and ET_o (mm) variations during the field experimentation which was not significant. It was observed that the soil moisture contents of deeper zones remained at a higher level than that of lower depths. Also, the temporal changes in the soil moisture contents were found to have been linearly increasing.

Table 2. Moisture content in the root zone soil profile before irrigation application

Soil profile	Depth, cm	Soil moisture content		
		Replications		
		θ_1	θ_2	θ_3
Upper	0-15	21.8	22.7	24.5
root zone	15-30	19.7	20.6	23.5
layer	30-45	17.4	18.4	20.8
Average		19.6	20.6	22.9
Middle	45-60	15.5	16.3	18.6
root zone	60-75	14.4	16.5	18.8
layer	75-90	14.5	17.4	18.8
	90-115	13.3	16.5	17.5
Average		14.4	16.7	18.4
Bottom	115-120	12.1	15.4	17.2
root zone	120-135	11.0	14.3	17.3
layer	135-150	9.4	11.2	17.0
Average	115-150	10.8	13.6	17.2
Average root zone	0-150	10.8	13.6	17.2

Profile soil moisture content after irrigation application

The soil moisture content θ, in different runs of border irrigation fitted well in exponential and logarithmic functions function given by equations 1 through 3.

The results are depicted in Table 2. The soil moisture content θ1, 1 week after the first run of border irrigation fitted well in exponential and logarithmic functions function given by equation 9 having the highest R^2 = 0.919; while all other models were inferior. However, the linear model was at par with the best fit model with R^2 = 0.907.

$$y = 21.76\, e^{-0.001\, x} \tag{9}$$

The soil moisture content θ2, as well the soil moisture content θ3, 1 week after the second run of border irrigation fitted well in logarithmic function as given by equation 10 having the highest R^2 = 0.866; while all other models were inferior.

$$y = -2.63 \ln(x) + 30.72 \tag{10}$$

The irrigation efficiencies as observed in the different runs of the experiment without and with crops are in line with the similar results reported by (Li, Rao, 2000; Liu *et al*., 2000; Liu, Kang, 2007; Liu *et al*., 2003). It is however, important to note that the irrigation efficiencies while having the similar trend as reported by other workers (Sayre, 2000; Hobbs, 2002; Juanjuan *et al*., 2010; Kurre *et al*., 2016) showed only marginal variations amounting to statistically non-significant change with the changing border widths. However, as the irrigation efficiencies are more dependent on the soil properties rather than the crop that was uniform at every growth stage (in three separate runs of the experiments). Further, the growth of the crop above and below ground, and the development of root system might result into substantial changes in the flow pattern thus, the soil moisture content, time taken by the advance curve to reach the other end of the border.

Table 3. Fitting the best mathematical model in root zone soil moisture variation in different runs.

Run No.	Models	R^2
1 week after the first run of border irrigation	$y = -0.061x + 20.94$	0.907
	$y = 21.76e^{-0.001x}$	0.919
	$y = -3.77 \ln(x) + 31.15$	0.858
1 week after the second run of border irrigation	$y = -0.04x + 23.32$	0.789
	$y = 23.39e^{-0.001x}$	0.811
	$y = -2.63\ln(x) + 30.72$	0.866
1 week after the third run of border irrigation	$y = -0.04x + 23.32$	0.789
	y = 23.39e-0.001x	0.811
	$y = -2.63\ln(x) + 30.72$	0.866

Hydraulics of border irrigation depends upon many edaphic and slope factors apart from the stream size and width of borders. Infiltration properties of the soil are among the most important factors in the design and management of the irrigation system but are often difficult to evaluate because of spatial and temporal variability of soil properties (Khanna, Malano, 2006; Juanjuan *et al*., 2010; Niel *et al*., 2014.) with sprinkler or drip irrigation systems (Howell, 2003). Infiltration rate also differs with each irrigation method for the same type of soil. Infiltration characteristics in surface irrigation systems affect the advance of water front and recession phase after time of cutoff. Therefore, this study focused on the evaluation of border method of irrigation under steady inflow and temporally varying infiltration conditions for growing wheat crop on sandy loam soils at IARI New Delhi with a stream of 1.5 l/s fixed discharge. The objective of the present study was to optimize the best border width for given conditions.

Conclusion

Based on the overall performance from all aspects (i.e. hydraulics, advance curve movement, soil properties and various irrigation efficiencies) the 4.0 m wide border size was adjudged as the best among all sizes that were tested with the given soil (sandy loam) and stream size of 1.5 l/s. After standardizing the stream size and border width combinations and deciding the appropriate cutoff ratios for different types of soils, it may be possible to come out with a general recommendation and standardize the techniques to enhance the project efficiencies at par with the advanced irrigation systems. However, for the WTC soil condition with a stream size of 1.5 l/s the best border size has been found to be a 4 m wide and 25 m long one.

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