



International Journal of
**Agricultural
Research**

ISSN 1816-4897



Academic
Journals Inc.

www.academicjournals.com



Research Article

Improving Water Application Efficiency of Irrigation Borders Using Modified Water Front Advance-time Relation

Prabeer Kumar Parhi

Center for Water Engineering and Management, Central University of Jharkhand, 835205 Brambe, India

Abstract

Background and Objective: Border strip method of irrigation is a widely used surface irrigation technique which is best adapted to crops like wheat, barley, fodder crops and legumes. The present study was aimed to design an irrigation border to maximize water application efficiency which is very important to meet the growing water needs. **Materials and Methods:** Using the modified water front advance-time relation, an irrigation border has been designed and its efficiency was evaluated. The derived design procedure ensured application of uniform depth of irrigation throughout the length of border thus maximizing water application efficiency of the irrigation borders. In the present study the required optimum border length, entrance stream size and the corresponding Manning's 'n' had been derived to achieve optimum irrigation water application efficiency. The derived design procedure has been applied to the wheat crop cultivated in sandy loam soil in the Ramiala irrigation command (Orissa, India) to determine entrance stream size and corresponding optimum border length. **Results:** The result of the study showed that the optimum border length and entrance stream size required are, respectively 40 m and $2906 \text{ cm}^3 \text{ min}^{-1} \text{ cm}^{-1}$ which gives maximum water application efficiency up to the tune of 83.32%. **Conclusion:** The modified design technique increases the water application efficiency of the irrigation borders, which appears very high as compared to the achieved efficiency of 66.5%, as available in the literature. The suggested method appears very simple and can be applied easily to crops having different root zone depths cultivated in different soils.

Key words: Border length, optimum stream size, water front advance-time relation, water application efficiency, irrigation command

Received: March 14, 2017

Accepted: May 15, 2017

Published: June 15, 2017

Citation: Prabeer Kumar Parhi, 2017. Improving water application efficiency of irrigation borders using modified water front advance-time relation. *Int. J. Agric. Res.*, 12: 115-122.

Corresponding Author: Prabeer Kumar Parhi, Center for Water Engineering and Management, Central University of Jharkhand, 835205 Brambe, India
Tel: 8102262455

Copyright: © 2017 Prabeer Kumar Parhi. This is an open access article distributed under the terms of the creative commons attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited.

Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

The border-strip method of surface irrigation is a widely used irrigation technique which is best adapted to crops like wheat, barley, fodder crops and legumes, where topography is flat¹. The design of border irrigation requires many input parameters and needs extensive engineering calculations and therefore, the experimental trial and error design is frequently resorted to Khanjani and Barani². A border irrigation system is designed for entrance stream size, the length of run or slope of the border in such a way that it can replenish the soil moisture in the root zone uniformly before it depletes beyond a specific limit. To derive the maximum application efficiency, the water is allowed to stay on the surface for a sufficiently long time to permit the desired amount of water to infiltrate into the soil¹. It is important to mention that in an existing field layout, the length or slope of the border cannot be altered and the entrance stream size forms to be the main controllable variable that can be designed to increase the efficiency of the system.

The study of surface irrigation system can be classified into two basic categories, namely design and analysis. While determination of water front advance with time is an analysis problem, computation of optimum stream size, to achieve maximum irrigation efficiency is a design problem. The analysis of flow in surface irrigation is complex due to the interactions of several variables such as infiltration, inflow rate and hydraulic roughness³. The design, however, is more complex due to interactions of these input variables and the involved output parameters like efficiencies, uniformities, deep percolation and runoff⁴.

The efforts in analysis and design of surface irrigation have predominated during last few decades. The studies of previous researchers⁵⁻¹¹ are only a few to cite among many others. The design of surface irrigation is however has been summarized in a few reports only. For example, Hall¹² developed a design procedure based on the calculation of rate of advance from the observed or expected infiltration characteristics, allowable range of slope, possible value of roughness and maximum allowable stream size, which was further modified and simplified by Michael¹. The Soil Conservation Service¹³ developed a design procedure for several types of surface irrigation systems. Walker and Skogerboe¹⁴ proposed a design procedure for graded borders, furrows and basins. Clemmens *et al.*¹⁵ developed a dimensionless solution for level basin design. Using Kostiakov infiltration model, Alazba,⁴ presented a border design, applicable to sloping open-ended borders only. Khanjani and

Barani² proposed a system-based border irrigation design technique using border irrigation storage and distribution efficiencies, border slope and length, inflow rate, cutoff time and Manning's roughness coefficient as constraints.

Using the water front advance-time relationship, Michael and Pandya⁷ and Michael¹ modified the design procedure suggested by Hall⁹. However, the complexity of equations used for the determination of water front advance-time relation makes the existing design procedure more complex and less popular. In view of the above, the present study attempts to modify and simplify the Michael's¹ design procedure using water front advance-time relation which does not appear to have been reported in literature. Thus, the objective of the current study was to further modify the Michael's¹ technique for the design of the irrigation borders applying the water front advance-time relations of Parhi¹⁶ derived using Kostiakov (KT)¹⁷, modified Kostiakov (MKT)¹⁸ and improved modified Kostiakov (IMKT)¹⁹ infiltration models.

MATERIALS AND METHODS

Study area: The present study was carried out and applied to the field data of Ramial irrigation command (Orissa, India). The climate of the study area is tropical with fairly hot summer, moderately cold winter and humid rainy season. The temperature of the area varies from a minimum of 12.9°C to a maximum of 39.9°C having average annual rainfall as 1182 mm. The rainfall is confined from June-October during which 90% of annual rainfall is received. The rainfall received in rest of the period is of no agro-irrigational interest as much of it is lost in infiltration and evaporation. As border irrigation system is most suited for the wheat crop, which is largely cultivated during Rabi season, a border irrigation system is designed using the field data and applied to this area to achieve maximum irrigation efficiency.

Data used: Due to non-availability of infiltration data of the study area, which is essential for the design of a border irrigation system, the data employed here is taken from the infiltration tests carried out by Michael²⁰, on sandy loam soil (same to the study area). The data has been used to determine the functional form of $y(t)$. The field capacity and wilting point of the sandy loam soil in study area have been considered as 16 and 4%, respectively²¹, thus making the water holding capacity of soil as 12% (12 cm m⁻¹ depth). The root zone depth of wheat crop has been taken as 1-1.5 m and average being 1.25 m²².

Parameter estimation of infiltration data: To find the equation of a specified type that best fits the set of observations, the optimal values of parameters of various infiltration models i.e. KT, MKT and IMKT, were estimated using the method of least squares. The method suggests that, for the best fits, the sum of the squares of differences between the observed and the corresponding estimated values are minimum²³, which can be expressed as:

$$\text{Min } Z = \sum_{i=1}^N \{f_{\text{obs}}(i) - f_{\text{com}}(i)\}^2 \quad (1)$$

where, Z is the error, N is the number of observations or times, $f_{\text{obs}}(i)$ is the observed infiltration rate at i^{th} time and $f_{\text{com}}(i)$ is the computed infiltration rate at i^{th} time.

In this study, the software package, Language for Interactive General Optimizer (LINGO) was used to minimize the errors. The accumulated infiltration-time relationship, resulting from the employment of above mentioned models, exhibited a form as $y = 1.459t^{0.697}$. This appears to be in the form KT, where y equals accumulated infiltration at any time t.

Performance evaluation: Among the several statistical measures available for evaluating the performance of a model, such as correlation coefficient, relative error, standard error etc., the Nash and Sutcliffe²⁴ efficiency is most frequently used²³ and it has been employed in this study.

The efficiencies resulting from the employment of KT, MKT and IMKT models to infiltration data in a wheat field in predicting accumulated infiltration-time relationship, performed identically and yielded 99.9% efficiency value, exhibiting a more than satisfactory performance.

Water front advance-time relation: As KT, MKT and IKMT showed identical results in predicting the accumulated infiltration-time relationship, the water front advance-time relationship is computed using KT, because it provides the simplest form of water front advance-time relationship, converges satisfactorily and rapidly for almost all values of t giving satisfactory results¹⁹. In the context of present discussion it is pertinent to present here the water front advance-time relationship using KT which forms the most important component in design of border irrigation system¹⁹, which can be written as:

$$\frac{x}{q} = \frac{1}{b+d} \left[t - \left(\frac{ct^{n+1}}{\Gamma(n+2)} \right) + \left(\frac{c^2t^{2n+1}}{\Gamma(2n+2)} \right) - \left(\frac{c^3t^{3n+1}}{\Gamma(3n+2)} \right) + \left(\frac{c^4t^{4n+1}}{\Gamma(4n+2)} \right) - \dots + \dots \infty \right] \quad (2)$$

and

$$\frac{x}{q} = \frac{1}{k} \left[\frac{t^{1-n}}{\Gamma(2-n)} - \left(\frac{c_1t^{1-2n}}{\Gamma(2-2n)} \right) + \left(\frac{c_1^2t^{1-3n}}{\Gamma(2-3n)} \right) - \left(\frac{c_1^3t^{1-4n}}{\Gamma(2-4n)} \right) + \left(\frac{c_1^4t^{1-5n}}{\Gamma(2-5n)} \right) - \dots + \dots \infty \right] \quad (3)$$

where, q is the constant rate of flow per unit width introduced at the upstream end of the border ($\text{cm}^2 \text{min}^{-1} \text{cm}^{-1}$ width of border), t is the total time for which irrigation water has been applied (min), x is the distance, the irrigation stream has advanced in time 't' (cm), d is the average depth of flow over the ground surface (cm):

$$c = \frac{k}{(b+d)}, c_1 = \frac{b+d}{k} = \frac{1}{c}, m\Gamma(n+1) = k$$

and m, n and b are infiltration parameters determined by optimization. The Eq. 2 and 3 works best for small and large values of t, respectively.

RESULTS AND DISCUSSION

Design of border irrigation system: The depth of water required to replenish the soil moisture in the root zone to field capacity is calculated as the product of water holding capacity and average depth of root zone (15 cm in the present study). Considering different possible values of stream size (q) as 3000, 3200, 3400 and 3600 $\text{cm}^3 \text{min}^{-1} \text{cm}^{-1}$ width, the approximate values of Manning's roughness 'n' is calculated using equation¹ as:

$$v = \frac{R^{2/3}s^{1/2}}{n} \quad (4)$$

where, v is the velocity (m sec^{-1}), R is the hydraulic radius (m) s is the soil surface slope (%). The values of Manning's 'n' computed using Eq. 4 for a vegetated (wheat crop) field having sandy loam soil are 0.257, 0.256, 0.255 and 0.254, respectively for stream sizes 3000, 3200, 3400 and 3600 $\text{cm}^3 \text{min}^{-1} \text{cm}^{-1}$ width.

Using the values of 'q' and 'n', the depth 'd_o' at the upstream end of the border is calculated¹ as.

$$n = \frac{d^{5/3}s^{1/2}}{q} \quad (5)$$

where, q is the entrance stream size.

Table 1: Calculation procedure for the estimation of average depth of flow (d) for 'q' and 'd_o' of 3000 cm³ min⁻¹ cm⁻¹ and 9.03 cm, respectively

Stream size (q)*	Depth at upstream end (d _o) (cm)	Time (min)	Accumulated infiltration(y _i) (cm)	Distance advanced L(cm)	Volume of water infiltrated (q _i)*	Stream size at any point down the border (q _o)*
3000	9.03	2	3.69	509.34	470.28	2529.72
2529.72	8.15	4	5.16	855.17	551.84	2448.16
2448.16	7.99	6	6.41	1176.12	628.69	2371.31
2371.31	7.84	8	7.54	1448.77	683.09	2316.91
2316.91	7.73	10	8.59	1690.73	726.17	2273.83
2273.83	7.64	12	9.57	1907.00	760.74	2239.26
2239.26	7.57	14	10.51	2102.63	789.19	2210.81
2210.81	7.52	16	11.40	2280.88	812.91	2187.09
2187.09	7.47	18	12.27	2444.31	832.90	2167.10
2167.1	7.43	20	13.10	2595.02	849.91	2150.09
2150.09	7.39	22	13.91	2734.51	864.43	2135.57
2135.57	7.36	24	14.70	2864.14	876.90	2123.10
2123.1	7.34	26	15.46	2984.91	887.60	2112.40
2112.4	7.31	28	16.21	3097.72	896.80	2103.20
2103.2	7.29	30	16.95	3203.31	904.69	2095.31
2095.31	7.28	32	17.66	3302.24	911.42	2088.58
2088.58	7.26	34	18.37	3395.01	917.10	2082.90
2082.9	7.25	36	19.06	3481.95	921.83	2078.17
2078.17	7.24	38	19.74	3653.36	949.04	2050.96
2050.96	7.19	40	20.41	3729.20	951.55	2048.45
2048.45	7.18	42	21.07	3832.85	961.55	2038.45
2038.45	7.16	44	21.72	3919.64	967.61	2032.39
2032.39	7.15	46	22.37	4006.95	974.11	2025.89
2025.89	7.13	48	23.00	4090.11	979.88	2020.12
2020.12	7.12	50	23.62	4169.99	985.14	2014.86

*Unit cm³ min⁻¹ cm⁻¹

Table 2: Values of 'n' and 'd_o' for different values of 'q' under consideration

Stream size (q) (cm ³ min ⁻¹ cm ⁻¹)	Manning's roughness (n)	Depth at upstream end (d _o) (cm)	Average depth of flow (d) (cm)
3000	0.254	9.02	7.48
3200	0.255	9.36	7.77
3400	0.256	9.68	8.06
3600	0.257	10.00	8.35

Further, the flow depths d₁, d₂, d₃.... d_n at successive points along the border is calculated by considering the distance advanced at equal time increments using water front advance-time relation (Eq. 2, 3) and its average is taken as d. The water depth required at successive points down the border will decrease as the total flow along these points decrease. Hence the water depth is a function of the distance down the border. Thus the stream size (q_o), at any point down the border equals the difference between the entrance stream size (q) and the average rate of the volume of water (q_i) infiltrated over the area from the upstream of border.

In the present study considering the value of 'q' as 3000 cm³ min⁻¹ cm⁻¹ the approximate value of 'n' is estimated (using Eq. 4) as 0.257 for a wheat field. Subsequently using 'q' and 'n' as 3000 cm³ min⁻¹ cm⁻¹ and 0.257, the depth 'd_o' at the upstream end of the border is calculated (Eq. 5) as 9.02 cm. Further, using 'q' and 'd_o' as 3000 cm³ min⁻¹ cm⁻¹ and 9.02 cm, respectively, the depths d₁, d₂, d₃.... d_n up to 50 m length of border is estimated and the average depth of flow down the

border (d) is estimated as 7.48. Table 1 shows the detail calculation procedure involved in estimating the average depth of flow down the border for a 'q' and 'd_o' as 3000 cm³ min⁻¹ cm⁻¹ and 9.02 cm, respectively up to 50 m length of border and Table 2 shows the values of n, d_o and d for different values of q under consideration.

A family of advance curves is calculated applying Eq. 2 and 3, for different values of stream sizes (3000, 3200, 3400, 3600 cm³ min⁻¹ cm⁻¹) having different average depths of flow as 7.48, 7.77, 8.06 and 8.35 cm, respectively, using the computed infiltration parameters (m = 1.459, n = 0.697 and b = 1.328) for the soil in question. Figure 1 shows the family of advance curves showing the water front advance time relationship as a function of q, d and infiltration parameters.

Considering y_o, y_i and y_d, respectively as accumulated total depth of water entering the soil at any point, total depth of water entering the soil at upstream end of border and design depth of application of water corresponding to an infiltration opportunity time of 'T' for a border length 'L', the first design

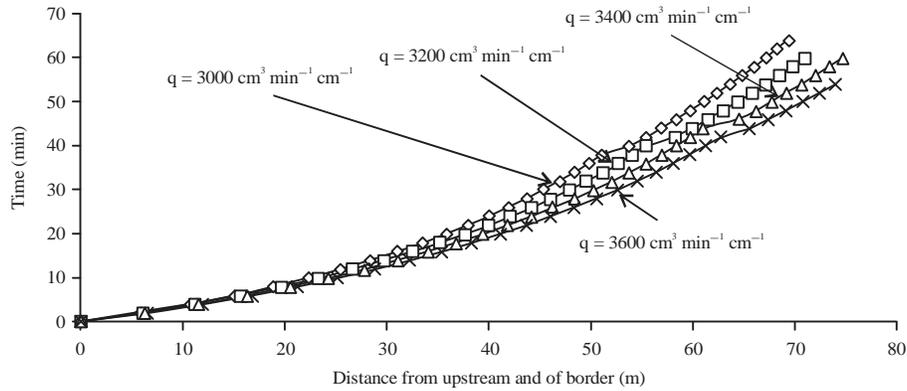


Fig. 1: Water front advance curves for different stream sizes (q)

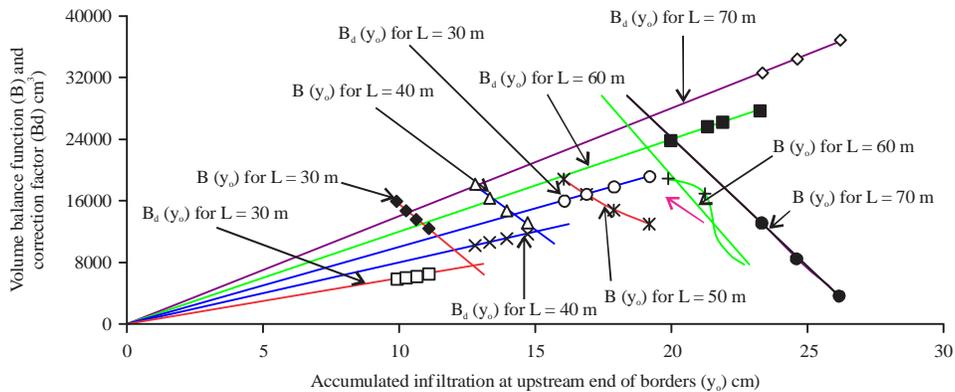


Fig. 2: Determination of optimum values of (L) and (q) using volume balance function

criteria needs to be satisfied is volume of water entered to the border till the advancing water front reaches the end must at least equal to volume required by the soil. This can be expressed as:

$$qT = yL \quad (6)$$

Further, a volume balance function (B), is derived expressing the difference between volume of water applied till the advancing water front reaches the end of the border and application of uniform depth (y_0) of water over the entire border length¹ as:

$$B = qT - y_0L \quad (7)$$

It is important to note that to allow for non-uniformities and non-parallel advance and recession curves, only values of ' B ' greater than some minimum values of ' B_d ' can accomplish adequate irrigation¹, which can be expressed as:

$$B_d = f_1 yL \quad (8)$$

where, f_1 is a measure of excess water entered to the border.

Assuming border length selected for design trials as 30, 40, 50, 60 and 70 m, the values of T , y_0 , B and B_d for different border lengths and entrance stream sizes are estimated. The value of f_1 is determined by experience and from the factors affecting the lack of parallelism of advance and recession curves¹⁶. To allow for non-parallelism of advance and recession curves, considering the factor of safety or a measure of the excess water (f_1) as 0.2¹⁶, the values of B_d are calculated for different border lengths and entrance stream sizes. Table 3 shows the values of T , y_0 , B and B_d for different border lengths and entrance stream sizes. Considering, B and B_d as ordinate against y_0 as abscissa with length of border (L) as parameters, a plot of B and B_d versus y_0 is obtained which is shown in Fig. 2. The intersection of $B(y_0)$ and $B_d(y_0)$ for a given length represents the minimum value of B which is acceptable for that length, since lower values would not provide adequate irrigation to all parts of the field. This point also represents the point of optimum application efficiency. In Fig. 2, the point of

Table 3: Values of T , y_o , B and B_d for different trial border lengths and stream sizes
Entrance stream size (q) ($\text{cm}^3 \text{min}^{-1} \text{cm}^{-1}$)

Border length (m)	3000				3200				3400				3600			
	T (min)	y_o (cm)	B (cm^3)	B_d (cm^3)	T (min)	y_o (cm)	B (cm^3)	B_d (cm^3)	T (min)	y_o (cm)	B (cm^3)	B_d (cm^3)	T (min)	y_o (cm)	B (cm^3)	B_d (cm^3)
30	15.2	11.1	12514	6641	14.2	10.6	13680	6366	13.4	10.2	14848	6138	12.7	9.9	15970	5939
40	24.0	14.7	13201	11753	22.0	13.9	14857	11146	20.5	13.3	16494	10646	19.2	12.8	18081	16025
50	36.3	19.2	13092	19168	32.6	17.8	14907	17869	29.7	16.8	16869	16852	27.5	16.0	18862	16025
60	48.4	23.1	6440	27746	44.1	21.7	10633	26122	42.4	21.2	17007	25464	38.3	19.8	18911	23836
70	65.2	28.1	-1503	39413	58.4	26.2	3695	36653	53.1	24.6	8561	34436	49.0	23.3	13250	32650

T , y_o , B and B_d , respectively represents infiltration opportunity time, total depth of water entering the soil at upstream end and volume balance function which is derived expressing the difference between volumes of water applied till the advancing water front reaches the end of the border and some minimum values of B that can accomplish adequate irrigation

intersections of $B(y_o)$ and $B_d(y_o)$ for 30, 40, 50, 60 and 70 m lengths are shown. From the Fig. 2, it is clear that if the design depth of application of each irrigation is 12.8 cm, the optimum border length is 30 m and if the depth of application is 15 cm, the optimum border length is 40 m and so on.

Considering the wheat crop on sandy loam soil under study, for which depth of water required to replenish the soil moisture in the root zone to field capacity is 15 cm, the optimum border length required is 40 m. Figure 3 clearly shows the intersection of $B(y_o)$ and $B_d(y_o)$ for 40 m length and the point of optimum application efficiency for wheat crop. Considering the optimum border length (L) as 40 m, design depth of application (y_d) as 15 cm, time of application (T) as 24.78 minute and volume balance function (B) as 12000 cm^3 (determined from Fig. 3), the optimum stream size is determined using Eq. 7, which equals to $2906 \text{ cm}^3 \text{min}^{-1} \text{cm}^{-1}$. The optimum border length and entrance stream size required to achieve maximum water application efficiency for crops other than wheat having different root zone depth, thus having different depth of water (y_o) required to replenish the soil moisture in the root zone to field capacity, can be determined from the Fig. 2.

Application efficiency: The water application efficiency (E_a) is a measure of how efficiently the water is applied to the field. The definition of E_a has been fairly standardized²⁵ as:

$$E_a = \frac{\text{Volume of water added to the root zone}}{\text{Volume of water applied to the field}} \quad (9)$$

Using the notations as used in the text, volume of water added to the root zone and volume of water applied to the field corresponds to ($y_d L$) and (qT), respectively. Hence E_a can be represented as:

$$E_a = \frac{y_d L}{qT}$$

Considering the derived values of y_d , L , q and T as 15 cm, 40 m, $2906 \text{ cm}^3 \text{min}^{-1} \text{cm}^{-1}$, the water application efficiency equals 83.32%.

The results of this study give an application efficiency of the designed irrigation borders as 83.32%, which appears very significant as compared to the earlier studies carried out by different researchers²⁶⁻²⁹. Mangrio *et al.*²⁶ studied the average water application efficiency under border irrigation method using different techniques and observed the average value as 67%. According to FAO²⁷, the water application efficiency for

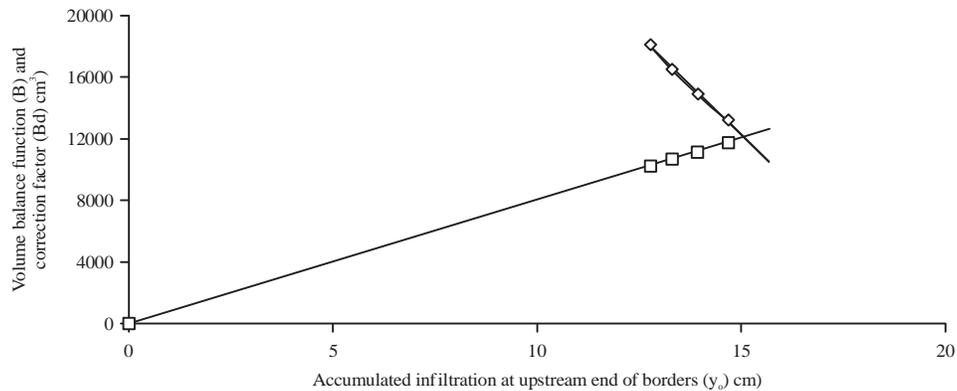


Fig. 3: Determination of optimum value of (L) and (q) using volume balance function for wheat

Figure shows the intersection of B (y_e) and B_d (y_e) for 40 m length and the point of optimum application efficiency for wheat crop. Considering the optimum border length (L) as 40 m, design depth of application (y_d) as 15 cm, time of application (T) as 24.78 min and volume balance function (B) determined from graph as 12000 cm^3 , so that Eq. 9 can be applied to determine water application efficiency

border and furrow irrigation methods is up to 60%. The study carried out by Shaikh *et al.*²⁸, in different areas reveals that application efficiencies for border irrigation method are within the ranges of 65-68% under medium textured soils. Further a study carried out on irrigation borders by Zerihun *et al.*²⁹ achieved an application efficiency of 66.5%. In the above context, the maximum application efficiency that can be achieved is around 68% which is significantly low as compared to 83.32% achieved in the present study. Hence the present design methodology appears most appropriate in the of growing water needs of present days.

CONCLUSION

Following conclusions can be derived from the present study.

- The optimum border length and entrance stream size required to achieve maximum water application efficiency for wheat crop in sandy loam soil in the study area are 40 m and 2906 $\text{cm}^3 \text{min}^{-1} \text{cm}^{-1}$, respectively that gives application efficiency of 83.32%
- The method is simple having easy field applicability as the plot of B and B_d versus y_e , can be used to determine optimum border length and entrance stream size required to achieve maximum water application efficiency for various crops having different root zone depth
- As prediction of water front advance-time relationship accurately and easily forms an important component in the efficient design of border irrigation system, use of modified technique to predict the water front

advance-time relationship make the procedure simpler thus enhancing its field adaptability

- The derived simplified method is also applicable to crops different from wheat and having different root zone depths

SIGNIFICANCE STATEMENTS

This study discovers the methodology for the design of an irrigation border for all types of soils such that the water application efficiency becomes maximum. This study will be beneficial to researchers to design irrigation borders in the most efficient manner which many researchers were not able to explore.

REFERENCES

1. Michael, A.M., 1982. Irrigation: Theory and Practice. Orient Long Men Co., New Delhi, India, ISBN-13: 9780706915136, Pages: 801.
2. Khanjani, M.J. and G.A. Barani, 1999. Optimum design of border irrigation system. J. Am. Water Resour. Assoc., 35: 787-792.
3. Maheshwari, B.L. and T.A. McMahon, 1992. Modeling shallow overland flow in surface irrigation. J. Irrig. Drain. Eng., 118: 201-217.
4. Alazba, A.A., 1997. Design procedure for border irrigation. Irrig. Sci., 18: 33-43.
5. Davis, J.R., 1961. Estimating rate of advance for irrigation furrows. Trans. Am. Soc. Agric. Eng., 4: 52-54.
6. Fok, Y.S. and A.A. Bishop, 1965. Analysis of water advance in surface irrigation. J. Irrig. Drain. Div., 91: 99-116.
7. Michael, A.M. and A.C. Pandya, 1971. Water front advance in irrigation borders. J. Agric. Eng. Res., 16: 62-71.

8. Clemmens, A.J. and T. Strelkoff, 1979. Dimensionless advance for level-basin irrigation. *J. Irrig. Drain. Divis.*, 105: 259-273.
9. Bishop, A.A., G.J. Poole, N.L. Allen and W.R. Walker, 1981. Furrow advance rates under surge flow systems. *J. Irrig. Drain. Div.*, 107: 257-264.
10. Sherman, B. and V.P. Singh, 1982. A kinematic model for surface irrigation: An extension. *Water Resour. Res.*, 18: 659-667.
11. Singh, V. and S.M. Bhallamudi, 1996. Complete hydrodynamic border-strip irrigation model. *J. Irrig. Drain. Eng.*, 122: 189-197.
12. Hall, W.A., 1960. Design of irrigation border checks. *Agric. Eng.*, 41: 439-442.
13. USDA., 1974. Border Irrigation. In: SCS National Engineering Handbook, USDA (Eds.). Section 15, Chapter 4, Soil Conservation Service (SCS), U.S. Department of Agriculture, Washington, DC., USA.
14. Walker, W.R. and G.V. Skogerboe, 1987. *Surface Irrigation: Theory and Practice*. Prentice-Hall Inc., Englewood Cliffs, NJ., USA., ISBN-13: 9780138779290, Pages: 386.
15. Clemmens, A.J., T. Strelkoff and A.R. Dedrick, 1981. Development of solutions for level-basin design. *J. Irrig. Drain. Divis.*, 107: 265-279.
16. Parhi, P.K., 2016. An improvement to the waterfront advance-time relation for irrigation borders. *Irrig. Drain.*, 65: 568-573.
17. Kostiakov, A.N., 1932. On the dynamics of the coefficient of water-percolation in soils and on the necessity of studying it from a dynamic point of view for purposes of amelioration. *Transactions of 6th Committee International Society of Soil Science, Russia, Part A*, pp: 17-21.
18. Smith, R.E., 1972. The infiltration envelope: Results from a theoretical infiltrometer. *J. Hydrol.*, 17: 1-22.
19. Parhi, P.K., S.K. Mishra and R. Singh, 2007. A modification to kostiakov and modified kostiakov infiltration models. *Water Resour. Manage.*, 21: 1973-1989.
20. Michael, A.M., 1968. Evaluation of hydraulic characteristics influencing border irrigation design. Ph.D. Thesis, Department of Agriculture and Engineering, Indian Institute of Technology, Kharagpur, India.
21. Lenka, D., 1973. Water requirement of crops in Orissa. Orissa University of Agriculture and Technology, Bhubaneswer, Orissa, India.
22. FAO., 1977. Guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper No. 24, Revised 1977, Food and Agriculture Organization, Rome, Italy, pp: 1-179.
23. Mishra, S.K. and V.P. Singh, 2003. Soil Conservation Service Curve Number (SCS-CN) Methodology. 1st Edn., Kluwer Academic Publishers, Dordrecht, The Netherlands, ISBN-13: 9781402011320, Pages: 516.
24. Nash, J.E. and J.V. Sutcliffe, 1970. River flow forecasting through conceptual models part I-A discussion of principles. *J. Hydrol.*, 10: 282-290.
25. FAO., 1989. Guidelines for designing and evaluating surface irrigation systems. FAO Irrigation and Drainage Paper 45, Food and Agricultural Organization, Rome, Italy, pp: 1-137.
26. Mangrio, M.A., M.S. Mirjat, N. Leghari, N.H. Zardari and I.A. Shaikh, 2015. Evaluating water application efficiencies of surface irrigation methods at farmer's field. *Pak. J. Agric. Agric. Eng. Vet. Sci.*, 31: 279-288.
27. FAO., 1989. Annex-I: Irrigation efficiencies. In: *Irrigation Water Management: Irrigation Scheduling, Training Manual No. 4*, FAO., Rome, Italy. <http://www.fao.org/docrep/t7202e/t7202e08.htm>
28. Shaikh, I.A., A. Wayayok, A.F.B. Abdullah, A.B.M. Soom and M. Mangrio, 2015. Assessment of water application losses through irrigation surveys: A case study of Mirpurkhas subdivision, Jamrao irrigation scheme, Sindh, Pakistan. *Indian J. Sci. Technol.*, 8: 1-15.
29. Zerihun, D., C.A. Sanchez, K.L. Farrell-Poe and M. Yitayew, 2005. Analysis and design of border irrigation systems. *Trans. ASAE*, 48: 1751-1764.