The Effects of Three Furrow Shapes on Water Advance Characteristics, Application Efficiency, Deep Percolation and Tail Water Run-off

Dlamini, M. V.

Department of Agricultural and Biosystems Engineering, Faculty of Agriculture, University of Eswatini, Private Bag, Luyengo, Luyengo, M205. Swaziland.

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***Abstract*—** *Furrow irrigation is considered to be inefficient when compared to most pressurized irrigation systems. The objective of this research was to determine if different furrow shapes have different impacts on water management practices such as application efficiency, deep percolation ratio and tail water runoff. Three furrow shapes, a triangular (V-shaped), rectangular (R) and trapezoidal (T_p) shaped were evaluated and the results were compared with output from SIRMOD II. The parameters calculated from field data were not very different from those determined by the model. This indicated that the model predicted the volume balance of the field data with reasonable accuracy. It was observed that the time of advance was shorter for the triangular shaped furrow and much longer for the rectangular shaped furrow. Performance efficiency parameters were good for the trapezoidal and triangular shaped furrows and very poor for the rectangular furrow. Tail water ratio (TWR) was much higher in the triangular furrow and lower in the rectangular furrow. Where there was no deep percolation ratio, the model failed to return a reasonable value.*

Keywords*— *Advance, recession, SIRMOD II, infiltration, application efficiency, deep percolation, run-off.

I. INTRODUCTION

Furrow irrigation is probably the oldest and most widely used method for applying irrigation water to many field crops and vegetables worldwide (Childs et al., 1993; Walker and Skogerboe, 1989; Nie et al., 2018, Dlamini, 2020). Lima et al. (2014) observed that surface irrigation systems still remain the most used irrigation system worldwide mainly due to their energy saving capacity and ease of operation but they show low performance level as a consequence to the general design and inadequate management. This observation was also made by Lamaddalena et al. (2021). According to Spencer et al. (2019) the two primary factors causing inefficiencies in furrow irrigation are deep percolation losses and tail water runoff and are the two major constraints in furrow irrigation practices. Eldeiry et al. (2005) although measured various parameters including furrow geometry, in their study they concluded that the length of the furrow and its inlet inflow are the main factors affecting application efficiency. They observed that when using longer furrow lengths the irrigation system was less sensitive to variations in furrow inflow, furrow shape, field slope, and roughness. However, where longer furrow lengths are not possible, the application of water should be carefully controlled to maintain high efficiencies. In free ending furrow irrigation, the recession phase was very fast in the entire field compared to the advance. Thus, the time of advance becomes the main contributor to the water application in the furrow. Haddad and Bouhadef (2012) studied the impact of geometric shape of farming grooves on sediment transport and found that there were variations among the shapes.

The results of Schwankl et al. (2000) indicated that variability of furrow physical characteristics, in decreasing order of their relative impact on furrow irrigation performance was: furrow inflow rate, infiltration, geometry, and roughness. The infiltration characteristics (Dlamini, 2021) also plays an important role in understanding the movement of water along the furrow, with furrow shape (Eldeiry et al. 2005) being a critical parameter for determining the advance time. The application efficiency (AE) and distribution uniformity (DU) are the main indicators to evaluate the overall performance of any surface irrigation event (Lamaddalena et al. 2021). Holzapfel et al. (2010) noted that efficient irrigation practices that minimize deep percolation will therefore minimize leaching of contaminants. A good correlation was obtained among performance irrigation parameters; application efficiency (AE), requirement efficiency (RE), requirement distribution efficiency (RDE), and total distribution efficiency (TDE) and the design or management variables for furrow irrigation.

The analysis of performance indices by Assefa et al, (2017), on furrow irrigation in sugarcane indicated that the effect of slope was not statistically significant except distribution uniformity and uniformity coefficient; furrow length and flow rate were highly significant on all performance indicators. All indices except deep percolation ratio and storage efficiency had shown an increasing trend as flow rate increases. In furrow irrigation in clayey soil, Eldeiry *et al.* (2004) found that furrow length and application discharge are the main management and design parameters affecting application efficiency. Alazba (1999) noted that furrow performance relies on many irrigation parameters that include furrow geometry (shape, size, length, and slope); soil characteristics (infiltration and roughness); and management parameters (flow rate, application time, and required depth).

Generally, reduced application efficiency with furrow irrigation occurs because of runoff or deep percolation (Hsiao et al., 2007). Although hard to eliminate, runoff can be controlled by tail water reuse systems, changing furrow stream size, or changing irrigation set time (Eduardo et al., 2010). Deep percolation reduces irrigation efficiency and increases pumping costs. In addition, chemicals applied to the soil surface to control pests and improve production can leach below the root zone and into the groundwater.

Uniform application of water using furrow irrigation is difficult to achieve. As water advances down a field, the opportunity time, or the time water has to infiltrate the soil, is greater at the upper end of the field than the lower end (Dlamini, 2001). Non-uniform furrow irrigation, a primary cause of deep percolation, is usually more pronounced during the first irrigation of the season. Early in the season, soil conditions are loose because the soil has not yet consolidated due to irrigation or rainfall. Cultivation and furrow construction loosen the soil further and encourage surface soil water evaporation. In addition, root activity early in the growing season depletes soil water in the top layers of the soil. All of these conditions can result in dry, loose soil making irrigation difficult. If moving water down the field is difficult, non-uniform irrigation will result, causing deep percolation of water below the root zone, particularly at the head end of the field.

Any process allowing water to advance in a furrow and reach the end of the field faster will help improve water distribution and obtain more uniform irrigation. Fornstrom et al. (1985) used a technique called furrow firming to improve the advance rate of water in a furrow study. Many models have been developed that simulates surface irrigation, but most on isolated irrigation events assuming that there is no spatial variation in field parameters (e.g. infiltration, roughness, slope and cross section). The objective of this study was to evaluate the effect of three furrow shapes (a rectangular (R), trapezoidal (Tp) and triangular (V)) on furrow performances; application efficiency, deep percolation and tail water runoff.

II. MATERIALS AND METHODS

Advance and recession measurements were carried out on three different furrows shapes, each 180 m long and spaced 1.4 m apart. There were two guard furrows for each measured furrow, one on either side bordering the furrow of interest. Three furrow shapes (a rectangular (R), trapezoidal (Tp) and triangular (V)) were evaluated for furrow performances; application efficiency, deep percolation and tail water runoff (Dlamini, 2001). It was essential to ensure that inflow did not vary with time.

The advance – recession set up consisted of two Washington State flumes (WSC), one placed five metres from the inlet used for measuring inflow and the other placed at the end of the furrow, used for measuring runoff (outflow). The first stake position, 00, was placed 3 m down the upper flume and the last stake placed at 180 m down the furrow, 3 m before the tail-water measuring flume. In the case of the first flume, this was done to ensure that the water was set to the desired flow rate before it reaches the 00 measuring position, and for the last flume, so that the backwater effect from the flume did not interfere with the last stake reading. During each irrigation event, a constant inflow (Issaka et al., 2015; Walker, 2003) of about 60 liters per minute was maintained. The water was supplied from a sprinkler hydrant and controlled to the desired flow rate using a 25 mm globe valve.

Wooden stakes were placed 30 m apart along the entire furrow. The time water was allowed into the furrow was noted. The movement of the advance was noted by recording the time water arrive at each wooden stake (station). This was done until the water had reached the last stake at 180 m of the furrow length. After the water had reached the end of each furrow, it was allowed to runoff for a fixed interval (a period of 15 minutes), the same for all the furrows. Recession (time) was taken as the time when the tail of water passed a wooden stake. A degree of subjective judgment is required for recession, but errors are small in magnitude when compared to the contact time.

A furrow profilometer instrument (Walker and Skoggerboe, 1987; Dlamini, 2001) was used to measure the furrow profile before the first irrigation and after each irrigation event to determine any changes in furrow geometry. This device uses vertical rods to indicate relative soil surface elevations across a section of the furrow. Changes within the furrow were assumed to be due to the effect of irrigation and determined by calculating the cross sectional changes of the furrow.

Equations that relate the measured top width of each furrow shape were used to calculate the wetted perimeter, cross-sectional and applied water depth as functions of the distance along the furrow length.

Other measurements included the time water reached the furrow end T_L, the time to the middle of the furrow $T_{1/2L}$, the wetted perimeter at each point (w_p), the depth of flow (y) and the top width of the water level (T) at each station along the furrow. These measurements were required for the calculation of the Kostiakov-Lewis equation exponent "a" and the coefficient *"k"* as described by Baustista and Wallender (1985); Walker and Skoggerboe (1987). The equation was then used to determine the volume balance relationship of each furrow shape based on the time of advance and the top width of the water surface at each station (Izadi et al., 1977).

The steady or basic infiltration rates (f_o) were measured on another set of furrows by using the inflow –outflow method (Dlamini, 2001).

III. RESULTS AND DISCUSSION

The actual shapes of the furrows as measured in the field situation are shown in Fig. 1 for the triangular, Fig. 2 for the trapezoidal, and Fig. 3 for the rectangular shape. It is noted that it was not possible to get a perfect triangular (V shape), trapezoidal and a rectangular shape because during furrow forming the soil was dry and tended to fall back after the implement has passed, meaning that the furrows did not maintain a constant shape for the entire furrow length.

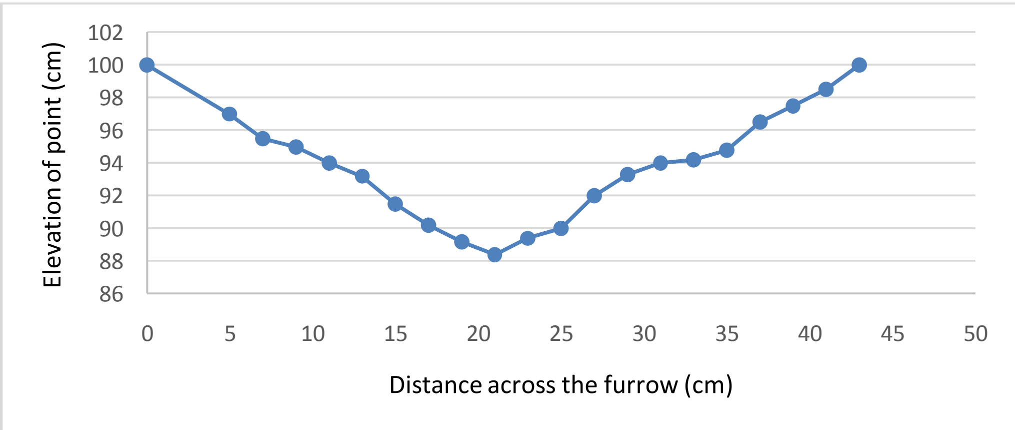

FIGURE 1: Average Geometry of the Triangular (V shape) Furrow (Measured Using the Profilometer Instrument) Before Irrigation at USU Greenville Farm, Logan during Summer

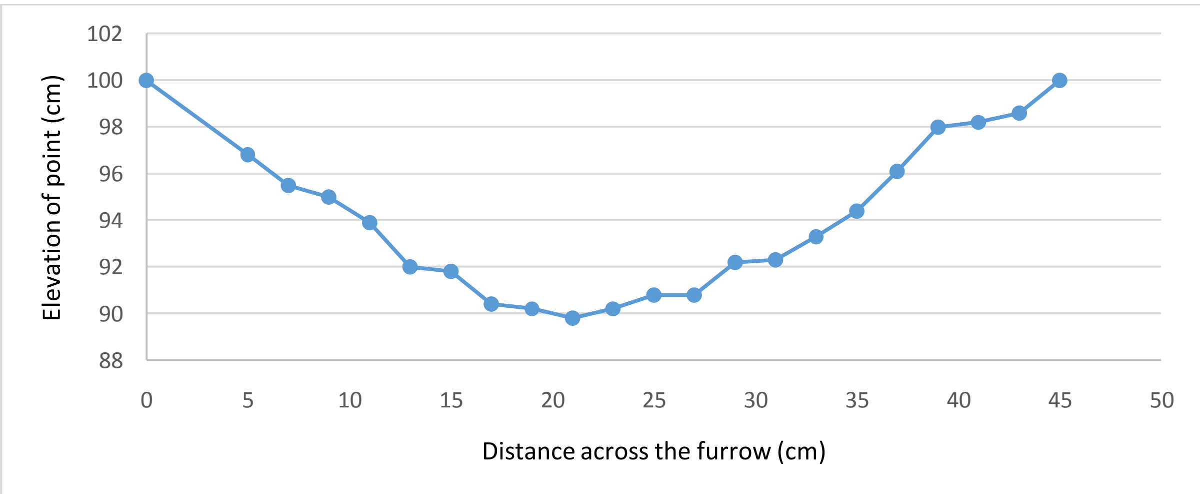

FIGURE 2: Average Geometry of the Trapezoidal Furrow (Measured Using the Profilometer Instrument) Before Irrigation at USU Greenville Farm, Logan during Summer

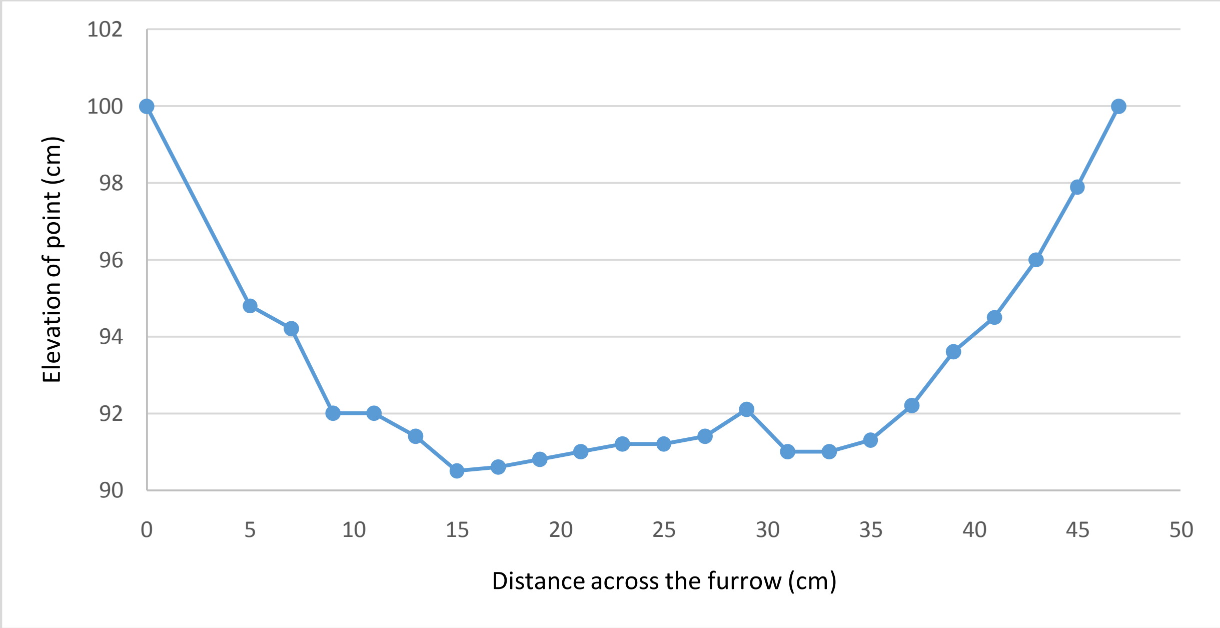

FIGURE 3: Average Geometry of the Rectangular Furrow (Measured Using the Profilometer Instrument) Before Irrigation at USU Greenville Farm, Logan during Summer

The design top width was 45 cm and a depth of 15 cm for all the furrow shapes. In an examination of the measured geometry of the furrows, it was observed that for the triangular and trapezoidal shapes about 3 cm of depth was lost due to soil refill, and about 4 cm for the rectangular shape even through the setting in the tractor implement was controlled and set at one position for all the shapes.

Table 1 gives the summary of the hydraulic properties of the three furrow shapes taken before the first irrigation event.

TABLE 1
SUMMARY OF THE HYDRAULIC PROPERTIES OF THE THREE FURROW SHAPES BEFORE IRRIGATION AT USU GREENVILLE FARM, LOGAN DURING SUMMER.

Hydraulic Property	Triangular (V)	Trapezoidal (Tp)	Rectangular (R)
Topwidth (T)	0.43	0.45	0.47
Depth (y)	0.12	0.11	0.10
Bottom Width (b)	0	0.16	0.20
Side Slope (m)	1.79	1.32	1.35
Calculated Properties			
Wetted perimeter (Wp)	0.49	0.52	0.47
Cross-sectional Area (A)	0.026	0.0336	0.0335
Hydraulic Radius (Rh)	0.052	0.064	0.071

The trapezoidal furrow had the largest wetted perimeter which was similar for both the rectangular and triangular. The triangular furrow shape had the smallest cross sectional area and hydraulic radius compared to the other two shapes.

Values of the basic intake rate for the first and second irrigation events obtained for each furrow shape within the measurement period are shown in Table 2. Since the experiment was done on a field with the same soil type, the basic intake rate was expected to be the same for all the furrow shapes. However, one observation to be made from the data is that the approach to the basic intake rate was faster for the triangular (V) shaped furrow and much slower for the rectangular (R) shaped furrow.

TABLE 2
DERIVED VALUES OF THE BASIC INTAKE RATE (cm/min) FOR THE FIRST AND SECOND IRRIGATION EVENTS FOR THE THREE FURROW SHAPES AT USU GREENVILLE FARM, LOGAN DURING SUMMER

Irrigation Event	Triangular (V)	Trapezoidal (Tp)	Rectangular (R)
1st Irrigation	0.00798	0.00826	0.0120
2nd Irrigation	0.00395	0.00446	0.0051

To solve the Kostiakov-Lewis equation (Dlamini, 2001; 2021), requires knowledge of the parameters "a" and "k". These values were calculated from the log-log transformation of the infiltration rate data by solving for the slope and intercept. Table 3 shows the values of "a" and "k" for each furrow shape for the first and second irrigation event. The data was analyzed based on three replicates to test if there were differences between irrigations events and within furrow shapes.

TABLE 3
KOSTIAKOV-LEWIS INFILTRATION PARAMETERS "a" AND "k" FOR THE THREE FURROW SHAPES AT USU GREENVILLE FARM, LOGAN DURING SUMMER.

Furrow shape/Irrig Event	Kostiakov-Lewis Infiltration Parameters			
	a		K (m^3/min^a)	
	1	2	1	2
Triangular (V)	0.307	0.281	0.00796	0.00493
Trapezoidal (T_p)	0.302	0.310	0.00916	0.00507
Rectangular (R)	0.376	0.295	0.00887	0.00658
Mean	0.328	0.295	0.00866**	0.00553**

***** Indicates that the values of the F statistic were significant at 1% level***

The results shows that differences between furrow shapes were not significant for values of "a", meaning that the values of "a" are independent of the furrow shape. The values did not significantly change from one irrigation event to another, though smaller for the second irrigation event. This might mean that the values of the parameter "a" are a function of the soil type rather than the furrow characteristics.

Values for the parameter "k" were smaller for the triangular shape furrow and larger for the rectangular. The values were also smaller for the second irrigation event.

The "a" and "k" values for each furrow were then applied in SIRMOD II model (Walker and Skogerboe, 1987; Walker, 2003) to simulate the performance of each irrigation, and then compare the measured and simulated characteristics.

To characterize the performance of each irrigation, the following measures of performance (equation 1-3) were calculated; application efficiency (E_a), deep percolation ratio (DPR) and tail water ratio (TWR)

$$E_a = \frac{Z_{req}\, X_d + V_{zi}}{Q_o\, t_{co}} * 100\% \tag{1}$$

$$DPR = \frac{V_{za} - Z_{req}\, X_d}{Q_o\, t_{co}} * 100\% \tag{2}$$

$$TWR = 100\% - E_a - DPR \tag{3}$$

where Z_{req} is the target depth of application, m; X_d is the distance of the advance, m; V_{zi} is the area inadequately irrigated, m^2; Q_o is the inflow into the furrow, m^3/min; t_{co} is the cut-off time, minutes; and V_{za} is the area adequately irrigated, m^2.

The outputs for the first and second irrigation events are summarized in table 4-6 for the triangular, trapezoidal and rectangular shape respectively.

TABLE 4
INFILTRATION PARAMETERS FOR THE TRIANGULAR (V) SHAPED FURROW FROM THE ADVANCE AND RECESSION MEASUREMENTS AT USU GREENVILLE FARM, DURING SUMMER

Parameter	Irrigation Event			
	1		2	
	Measured	SIRMOD II	Measured	SIRMOD II
Q_o (1/s)	1.0		1.0	
T_{co} (min)	51.3		36	
k (m^3/min^a)	0.00796		0.00493	
A	0.307		0.281	
T_L (min)	34.9	38.1	17.5	19.9
$T_{0.5L}$ (min)	12.5	14.3	8.1	9.3
Performance Measures				
Ea	76.8	79.9	37.1	40.3
DPR	0	-0.7	0	-0.9
TWR	23.2	20.8	62.9	60.6

TABLE 5
INFILTRATION PARAMETERS FOR THE TRAPEZOIDAL (T_p) SHAPED FURROW FROM THE ADVANCE AND RECESSION MEASUREMENTS AT USU GREENVILLE FARM, DURING SUMMER.

Parameter	Irrigation Event			
	1		2	
	Measured	SIRMOD II	Measured	SIRMOD II
Q_o (1/s)	1.0		1.0	
T_{co} (min)	86		56.3	
k (m^3/min^a)	0.00916		0.00507	
A	0.302		0.31	
T_L (min)	67.7	70.1	39.8	41.4
$T_{0.5L}$ (min)	19.9	20.6	14.5	15.5
Performance Measures				
Ea	70.8	72.5	75.5	78.8
DPR	15.9	21	0	-0.5
TWR	13.3	6.5	24.5	21.7

TABLE 6
INFILTRATION PARAMETERS FOR THE RECTANGULAR (R) SHAPED FURROW FROM THE ADVANCE AND RECESSION MEASUREMENTS AT USU GREENVILLE FARM, DURING SUMMER.

Parameter	Irrigation Event			
	1		2	
	Measured	SIRMOD II	Measured	SIRMOD II
Q_o (1/s)	1.0		1.0	
T_{co} (min)	184.0		75.0	
k (m^3/min^a)	0.00887		0.00658	
A	0.376		0.295	
T_L (min)	161.0	164.0	56.0	64.0
$T_{0.5L}$ (min)	50.6	51.1	20.5	24.7
Performance Measures				
Ea	34.2	34.1	77.3	81
DPR	57.4	62.3	1.8	2.8
TWR	8.4	3.6	20.9	16.2

The parameters calculated from field data were not very different from those determined by the model. This indicated that the model predicted the volume balance of the field data with reasonable accuracy. It was observed that the time of advance was shorter for the triangular shaped furrow and much longer for the rectangular shaped furrow. Performance efficiency parameters were good for the trapezoidal and triangular shaped furrows and very poor for the rectangular furrow. Tail water ratio (TWR) was much higher in the triangular furrow and lower in the rectangular furrow. Where there was no deep percolation ratio, the model failed to return a reasonable value.

IV. CONCLUSION

From the results of the study, it could be concluded that the parameters calculated from field data were not very different from those determined by the SIRMOD II model. This indicated that the model predicted the volume balance of the field data with reasonable accuracy. It was also observed that the time of advance was shorter for the triangular shaped furrow and much longer for the rectangular shaped furrow. Performance efficiency parameters were good for the trapezoidal and triangular shaped furrows and very poor for the rectangular furrow. The tail water ratio (TWR) was much higher in the triangular furrow and lower in the rectangular furrow. Where there was no deep percolation ratio, the model failed to return a reasonable value.

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