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Determination of Appropriate Furrow Length and Flow Rate for Furrow Irrigation Practice Under Semi-Arid Climate Condition at Middle Awash, Ethiopia

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Abstract: This article explains how to determine appropriate furrow length and flow rate for furrow irrigation system that is accurate and simple to use in semi-arid climates with clay soils. The experiment was carried out from April to November 2019 and April to November 2021. Cotton was grown in Middle Awash, werer, Ethiopia, thus field tests were conducted there. According to the analysis of variance, flow rate had a significant impact on crop water productivity ($p \leq 0.01$). Furrow length had a significant ($P \leq 0.05$) impact on crop water productivity. The combine analysis of flow rate shows that had a significant ($P \leq 0.05$) effect on water productivity of cotton. The yield and water productivity were significantly affected by the interaction of the two elements. Furrow length of 50 m combined with (1.2 lit/sec) flow rate for 35.6 minutes produced the highest water application efficiency (65.0%), water productivity (1.37 kg/m^3), and lint yield (6.86 ton/ha). The lowest water application efficiency (38.3%), with flow rate (1.6 lit/sec) for 9.75 minutes, and water productivity (0.85 kg/m^3) were achieved from 10 m furrow length. The result concludes that as the furrow length increases the water productivity increases this in turn increase the yield of cotton and decreases water loss.

Keywords: Application Efficiency, Distribution Uniformity, Water Productivity, Cotton, Yield

1. Introduction

Surface irrigation, in which water is dispersed over the field via overland flow, is the most common type of water application to agricultural lands. Because of its inexpensive equipment and energy costs, furrow irrigation is a popular surface irrigation method [1]. Furrow irrigation is the finest technique of surface irrigation because it provides adequate aeration in the root zone [2]. Despite its widespread use, the system has low irrigation efficiency and uniformities, which can lead to lower crop yields [3-6]. In surface irrigation, water losses might amount to as much as 40% of the entire water supply [7], this low efficiency may have occurred as a result of inadequate design and administration [8, 9]. Various management strategies and field layouts can be adopted to improve the irrigation efficiency and/or uniformity of a surface irrigation system during an evaluation.

The selection of an intake flow rate (Qmax) that maximizes application efficiency (Ea) is the most important challenge in the design of surface irrigation systems. According to the reports of [10-13] inflow rate and cut-off time are the most effective parameters of furrow irrigation design. Morris *et al*. (2015) suggested that inflow rate of the range of 2 to 7 lit/sec and cut-off time from 50 to 300 min were suitable for the best performance. According to [14-16], slope, length, and cross-section are all essential geometrical factors for performance evaluation. With the correct field geometry, you may boost irrigation application efficiency by up to 26.7% [16].

Efficient application and distribution of water by furrow irrigation is dependent on furrow parameters such as inflow, soil texture, field slope, soil infiltration, plant coverage, roughness coefficient, field shape, irrigation management. To address these issues, the first priority is to improve water management. However, there is limited quantitative data on the Amibara irrigation scheme's system performance. The objective of this study was to generate information on furrow variables specifically flow rate and furrow length and their combination to enhance irrigation efficiency.

2. Materials and Methods

2.1. Description of Study Area

The study site was Middle Awash, Werer Agricultural Research Center, in Ethiopia's Awash River Valley, where there is a severe need for judicious water use and productive agriculture, particularly cotton and onion cultivation. The research center is 740 meters above sea level and is located at 9° 16' 8" latitude and 40° 9' 41" longitude. The area is classified as semi-arid due to its average annual rainfall of 590 mm and high evaporation rate of 2680 mm per annual. The average minimum and maximum temperatures are 19°C and 40.8°C respectively. The gradients are usually between 1 - 2%.

2.2. Treatment Arrangement

Furrow length and irrigation water flow rate are two variables in the experiment. The experiment was set up using a split plot in randomized complete block design. In the main plots, three levels of furrow length were assigned, and three levels of flow rate were assigned in sub plots. Treatments were allocated to each plot at random, and each block served as a replication.

Table 1. *Treatment arrangement.*

No	Treatment arrangement		
	Main plot Furrow length (m)	Sub plot Flow rate Q_{max} (%)	Flow rate (Qmax) (lit/sec)
1	10	50	0.8
2	30	75	1.2
3	50	100	1.6

2.3. Design of Surface Irrigation System

The volume balance model was chosen for this investigation because it has been shown to be accurate, requires little data, and relies on few assumptions. The volume balance model posits that water entering the field will travel a distance, X, toward the field's lower end at any given time (t). The inflow of water into the furrows at the field's entrance, Qo, is assumed to be constant, such that at time t, the product of Qo and t equals the volume of water on the soil surface, Vy (t), plus the volume infiltrated, Vz (t), both of which are time dependent. The factors employed in the mathematical models representing the complete process of surface irrigation to increase irrigation efficiency include field size, field slope, flow rate, cut-off time, soil-infiltration characteristics, and flow resistance. Advance time, recession time, infiltrated depths, and accompanying irrigation efficiencies and uniformities are all determined by interactions between the variables. The volume balance equation is as follows [14]:

$$Q_O t = V_t + V_Z t \quad (1)$$

$$V_y t = \sigma_y A_0 x \quad (2)$$

$$V_z(t) = \int_0^x z(s,t) ds W_f \quad (3)$$

Ā is the average area of the furrow shape, W_f is the furrow width, A_o is the cross-sectional flow area at the field entrance, y is the surface shape parameter, z (s, t) is the infiltrated volume per unit length throughout the advance length, and s is the distance travelled by the advancing front.

$$Q_o t = \sigma_y A_o x + \sigma_z x W_f \quad (4)$$

Where σ_z is the sub-surface shape parameter. The following two assumptions are applied to the volume balance model:-

I. In a furrow a simple power function can be employed to describe the waterfront's trajectory

$$x = pt^r \quad (5)$$

Where x is the distance that the front has advanced at time t, and r, and P are empirically fitted parameters.

II. The infiltration function has a Kostiakov-Lewis characteristic form [14].

$$Z = k\tau^\alpha + f_o \tau \quad (6)$$

Where Z is the volume of infiltrating water per unit length, τ denotes the opportunity time, f_o denotes the basic intake rate in terms of volume per unit length per unit time, and k and τ denote empirically fitted parameters. The volume balancing model can be stated as follows if these two assumptions in the Lewis-Milne equation are used [14].

$$Q_O t = \sigma_y A_o x + \sigma_z k t_x^a x + \frac{1}{(1+r)} f_0 t_x x \quad (7)$$

where,

Q_O inflow per furrow at the upstream end of the field (m^3/min)

t time from the start of inflow (min)

σ_y Surface flow shape factor from 0.77-0.80

A_o the flow area at the flow's upstream end at time t_x (m^2)

x the distance from the inlet that the advancing front has travelled in t_x minutes

σ_z subsurface shape factor

f_0 basic infiltration rate

k empirical parameters (m^2/min/m)

r power advance

a empirical coefficient

For determining parameters 'k' and 'α' of the infiltration function can be solved knowing the advance times corresponding to two locations as follows [14].

$$\alpha = \frac{\ln(\frac{V_L}{V_{0.5L}})}{\ln(\frac{t_L}{t_{0.5L}})} \quad (8)$$

where,

α empirical coefficients
V_L volume of water at the end of the field
$V_{0.5L}$ volume of water at the mid of the field
t_L the advance time at the end of the field
$t_{0.5L}$ the advance time at the mid of the field

$$\sigma_y = \frac{\bar{A}}{A_o} \quad (9)$$

Where σ_y is the subsurface water profile shape factor and σy is the surface water profile shape factor.

The maximum non-erosive flow rate was calculated using the method below, which took into account the farm's slope (furrow slope) and soil type [17].

$$Qo = \alpha S^{-\beta} \quad (10)$$

α coefficient which depend on soil texture (soil type)
Q_{max} maximum non erosive flow rate (lit/sec)
β coefficient which depend on soil texture (soil type)
S Furrow slope (%)

The relationship between the depth of water in the furrow and the matching top width was determined using the furrow geometry data. To approximate this relationship, we used Equation 10. The parameters α_1, α_2 can be determined by fitting data to the equation 11.

$$B = \alpha_1 y^{\alpha_2} \quad (11)$$

Where B denotes the top width of the water in the furrow, y denotes the depth of the water in the furrow, and α_1 and α_2 are the top width factor parameters.

The wetted perimeter factor parameters γ_1 and γ_2 can be calculated using the formula below.

$$WP = \gamma_1 y\gamma^2 \quad (12)$$

Where WP is the wetted perimeter of the furrow.

Parameter data for the advance function is needed to improve furrow irrigation performance [18].

$$T = t_s - \frac{Q_o t_s - \sigma_y A_o L - \sigma_z K t_s^{\alpha} L W_f - \frac{f_o t_s W_f}{1+r}}{Q_O - \frac{\sigma_Z \alpha K W_f}{t_s^{(1-\alpha)}} - \frac{f_o L W_f}{1+r}} \quad (13)$$

The application efficiency (Ea) is computed by dividing the volume of water necessary to fill the specified depth of water in the soil by the volume of water delivered to the furrow.

$$E_a = \frac{Z_{req} * L * W_f}{t_{co} Q_o} \quad (14)$$

t_{co} is the cut-off time in minutes, and Z_{req} is the needed depth in meters to be filled.

2.4. Water Distribution Efficiency (DU)

The ratio of the smallest accumulating depths in the distribution to the average depths of the entire distribution is commonly referred to as distribution uniformity [19].

$$\mathrm{DU_{lq}} = \frac{\text{Average low quarter depth } (\mathrm{d_{lq}})}{\text{Average depth of water accumulated in all elements } (\mathrm{d_{avg}})} \quad (15)$$

2.5. Inflow time (T)

To apply the greatest depth of application water to the test (optimal) furrow and its buffer furrows with the given optimal flow rate, the time of cutoff was computed as follows [20].

$$T = \frac{F_g * W * L}{60 * Q_O} \quad (16)$$

T Inflow time of cutoff (min),
L Furrow length (m),
W Furrow spacing (m),
F_g Gross depth of application (mm),
Q_o Flow rate (l/s).

The flow rate in the 90° V-notch was determined by using the equation developed by [21].

$$Q = C_e \frac{8}{15} \sqrt{2g}\, tan \frac{\theta}{2} h_e{}^{\frac{5}{2}} \quad (17)$$

Q flow rate in the Parshall flume
Ce Coefficient of discharge
h_e Height measured with respect to the vertex of the notch, cm

Molden defined water productivity as the physical mass of production or the economic value of production measured against gross inflow, net inflow, depleted water, process depleted water, or available water [22].

$$\text{Water productivity}\left(\frac{\text{kg}}{\text{m}^3}\right) = \frac{\text{Output from water use (kg)}}{\text{Water input (m}^3\text{)}} \quad (18)$$

2.6. Estimation of Infiltration Parameter

One of the most helpful infiltration equations in surface irrigation is the modified Kostiakov-Lewis equation [23]. In this investigation, the Kostiakov–Lewis equation was employed to determine cumulative infiltration, as illustrated below.

$$Z = kt^{\alpha} + f_o t \quad (19)$$

where,

Z cumulative infiltration in units of volume per length of the furrow
t elapse time of infiltration (min)
α, k empirical coefficients (α=dimensionless, k=m^3/min/m^{-1})
f_o Basic infiltration rate (m^{-3} $m^{-1}$$min^{-1}$)

The advance curve is a simple power function, found using the following equation [5, 14].

$$x = Pt^r \quad (20)$$

where,

x water front advance (m)
P fitting parameter
t time from start of inflow (min)
r fitting parameter

Kostiakov-Lewis parameters (α and k) were determined as follows:

$$k = \frac{V_L}{\sigma_Z t_L^{\alpha}} \quad (21)$$

where,

k empirical coefficients

V_L Volume of water at the end of the field

σ_Z surface profile coefficients

$$V_{0.5L} = \frac{Q_o t_{0.5L}}{0.5L} - \sigma_Z A_o - \frac{f_o t_{0.5L}}{1+r} \quad (22)$$

Where σ_y is surface profile shape factor (0.77); σ_z is subsurface profile shape factor; $t_{0.5L}$ and T_L are the advance times (min) at two points, x_1=0.5 L and x_2=L respectively.

$$\sigma_z = \frac{\alpha + r(1-\alpha)+1}{(1+\alpha)(1+r)} \quad (23)$$

2.7. Irrigation Performance Parameter

Application efficiency (AE), distribution uniformity (DU), and deep-percolation were the three performance criteria used in this study (DP). Soil moisture samples were taken with an Auger core sampler at three locations along the furrow and at three depths before and after irrigation (48 hours) (0-30, 30-60 and 60-90 cm).

$$AE = \frac{D_{ad}}{D_{ap}} * 100 \quad (24)$$

Where Dad, Dp, Zmin, Zav, and Ddp represent the depth of water added to the root zone (mm).

3. Result and Discussion

3.1. Characteristics of the Experimental Site

The trial was conducted in 2019 and 2021 at Werer Agricultural Research Center. The soil of the site categorized under clay soil texture. Table 2 gives the soil physical properties and textural class. The bulk density ranges from 1.19 to 1.23 g/cm^3.

Table 2. *Physical properties and soil texture of experimental field.*

Soil depth (cm)	FC (%)	PWP (%)	Available water (mm/m)	Drainage rate (cm/hr)	BD (g/cm^3)	Texture			
						Sand	Clay	Silt	Class
0-30	42	30	147.9	26.9	1.19	5.1	58.2	36.7	Clay
30-60	42	30	152.9	24.4	1.23	9.1	52.9	38	Clay
60-90	41	27	156.8	26.4	1.22	6.5	51.5	42	Silty clay

FC= field capacity, PWP=permanent wilting point, BD=Bulk density.

Figure 1 shows that the basic infiltration rate of soil of experimental site was 5.01 mm/hr, which was the maximum infiltration for the clay soil.

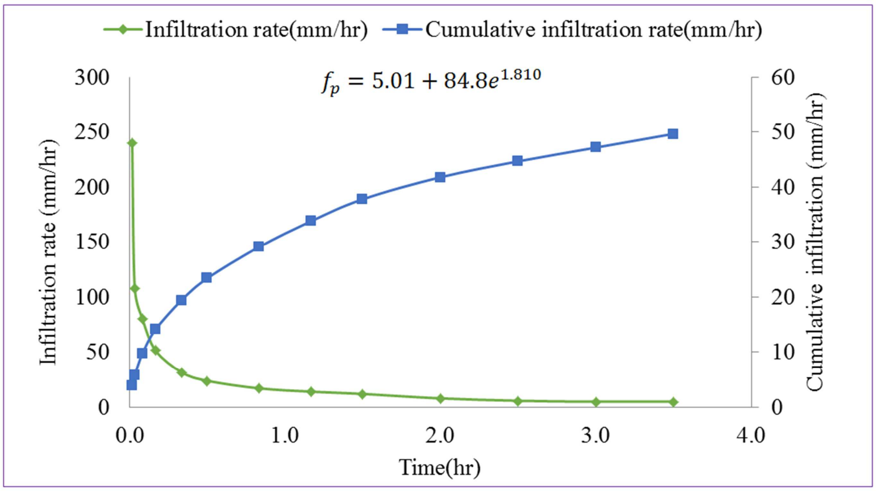

Figure 1. *Infiltration curve of experimental site.*

Table 3. *Soil chemical characteristics.*

Depth (cm)	Ece (ds/m)	pH	Soluble cations			SAR
			(Ca+Mg (meq/l)	meq/l (Na)	meq/l (k)	
0-30	0.44	7.70	1.5	12.1	1.01	13.8
30-60	0.61	7.50	1.2	15.6	1.03	21.5
60-90	0.79	7.50	1.5	13.7	1.1	17.4

Depth (cm)	Exchangable cations			OC (%)	TOC (%)	OM (%)	TN (%)	P (ppm)
	(Ca+Mg) cmol+/kg	K cmol+/kg	Na cmol+/kg					
0-30	46.3	5.8	18.5	0.77	0.95	1.64	0.08	14.73
30-60	44.7	4.3	16.2	0.61	0.8	1.38	0.07	16.63
60-90	43.3	2.6	14.3	0.52	0.69	1.19	0.06	17.06

OC= organic carbon, TOC= Total organic Carbon, OM= Organic matter, TN= Total nitrogen, SAR= Sodium Absorption Ratio.

3.2. Main Effect of Flow Rate and Furrow Length on Yield and Water Productivity

According to the analysis of variance, flow rate had a significant impact on crop water productivity ($p \leq 0.01$). Furrow length had a significant ($P \leq 0.05$) impact on crop water use efficiency. The maximum yield and water productivity was obtained from 50 m furrow length and from 1.2 l/sec flow rate. The result concludes that as the furrow length increases the water productivity increases this in turn increase the yield of cotton and decreases water loss. This result agreed with the results of [24, 25].

Table 4. *Main Effect of flow rate and furrow length.*

Furrow length	LY	BW	Cotton Seed Yield	WP
10 m	5.87^{b}	157.7^{b}	3.38^{b}	0.84^{b}
30 m	6.76^{a}	179.7^{a}	3.90^{ab}	0.97^{ab}
50 m	6.72^{a}	179.5^{a}	4.62^{a}	1.15^{a}
LSD (0.05)	0.67	19.3	0.78	0.20
CV	11.2	12.1	21.4	21.8
Flow rate				
0.8 l/s	6.58^{a}	167.6^{a}	3.5^{b}	0.88^{b}
1.2 l/s	6.54^{a}	174.2^{a}	4.2^{a}	1.06^{a}
1.6 l/s	6.58^{a}	175.2^{a}	4.1^{ab}	1.02^{ab}
LSD (0.05)	ns	ns	0.64	0.16
CV	11.9	13.6	16.05	13.4

SY= Seed yield (ton/ha), LY= Lint yield (ton/ha), BW= 30 Ball weight (gm), WP= water productivity (kg/m^3).

The combined analysis shows that there is a significance ($P \leq 0.05$) difference between furrow lengths in terms water productivity (Table 5). The highest water productivity was recorded from 50 m furrow length and minimum was recorded from 10 m. The furrow length had significant effect on water productivity of cotton and this result agrees with the achievements of [26].

Table 5. *Main effect of furrow length on Water Productivity.*

Treatment		Water Productivity (kg/m^3)		
		2019	2021	Combined mean
Furrow length (m)	10 m	0.86	0.82	0.84b
	30 m	1.02	0.93	0.97b
	50 m	1.18	1.12	1.15a
	Year*flow*Furrow Length	ns		
	LSD (5%)	0.16		
	CV	14.8		

LSD= least significance test, CV= Coefficient of Variation.

The combine analysis of flow rate shows that had a significant ($P \leq 0.05$) effect on water productivity of cotton (Table 6). The maximum water productivity was recorded from 1.6 l/s and minimum was recorded from 0.8 l/s. This result agrees with achievements of [26].

Table 6. *Main effect of Flow rate on water Productivity.*

Treatment		Water Productivity		
		2019	2021	Combined mean
Flow rate (l/s)	0.8 lit/sec	0.89	0.87	0.88b
	1.2 lit/sec	1.12	1.00	1.06ab
	1.6 lit/sec	1.06	0.99	1.02ab
	Year*flow*Furrow Length	ns		
	LSD (5%)	0.16		
	CV	14.6		

The combined analysis shows that the yield had significantly affected by furrow length (Table 7). The maximum cotton yield (seed yield + lint yield) was recorded from 50 m furrow length. Therefore, during using of long furrow length for crop production we have to take into consideration efficiency of water application. These includes cut-off, surge flow, and cut-back.

Table 7. *Main effect of Furrow length on cotton yield.*

Treatment		Cotton seed Yield (t/ha)		
		2019	2021	Combined mean
Furrow length (m)	10m	3.46	3.31	3.38[b]
	30 m	4.11	3.70	3.0[b]
	50 m	4.75	4.49	4.62[a]
	Year*flow*Furrow Length	ns		
	LSD (5%)	0.62		
	CV	19.4		

The combined analysis of flow rate shows that there is significant difference in harvest yield of cotton. The maximum yield was obtained from 50 m furrow length and the lowest was recorded from the shortest 10 m furrow length (Table 8).

Table 8. *Main effect of flow rate on yield of cotton.*

Treatment		Cotton seed Yield (t/ha)		
		2019	2021	Combined mean
Furrow length (m)	0.8 lit/sec	3.58	3.49	3.53[b]
	1.2 lit/sec	4.49	4.01	4.25[a]
	1.6 lit/sec	4.24	3.99	4.11[ab]
	Year*flow*Furrow Length	ns		
	LSD (5%)	0.66		
	CV	18.4		

3.3. The Effect of Furrow Length and Flow Rate on Water Productivity and Yield of Cotton

According to the results of ANOVA table there is a significant difference ($P \leq 0.05$) between the interaction effects of furrow length and flow rate (Table 9). The maximum water productivity of (1.37 kg/m^3) was recorded from 50 m furrow length combined with 1.2 lit/sec flow rate. Maximum lint and seed yield was also recorded from 50 m furrow length combined with 1.2 lit/sec flow rate. The highest water application efficiency of (65%) was recorded from 50 m furrow length with 1.2 lit/sec flow rate. On clay soil that furrow length and application discharge are the main factor affecting application efficiency [27]. Higher furrow length has maximum application efficiency and yield. The result in lined with results of [28-31].

Interaction effect of furrow length and flow rate on cotton yield was found to be significant ($P \leq 0.05$). Highest lint yield 6.86 ton/ha/month was obtained from combination of 50 m furrow length and 1.2 lit/sec flow rate. The least yield 5.48 ton/ha was obtained from combination of 50 m furrow length and 0.8 lit/sec flow rate.

Cotton lint yield, seed yield and water productivity were highly affected by interaction effect of furrow length and flow rate. Application efficiencies affected by the main plot factor furrow length. The higher the furrow length has maximum application efficiency and cotton lint and seed yield plus water productivity. Lint and seed yield was also affected by flow rate and furrow length. Given this and other economic benefits, it can be conclude that longer furrow length and highest flow rate is better for cotton production.

Table 9. *Interaction effect furrow length and flow rate on yield and water productivity of cotton.*

No	Treatment	AE (%)	DU (%)	WP (kg/m^3)	Advance time (min)	
	Furrow length (m) and flow rate (l/sec)				$T_{0.5L}$	T_L
1	10 m_Qmax_50%	43.8	55.6	0.89[bc]	1.44	3.09
2	10 m_Qmax_75%	56.6	49.6	0.78[c]	3.15	7.17
3	10m_ Qmax _100%	38.3	68.1	0.85[bc]	4.12	3.07
4	30 m_ Qmax _50%	64.1	61.6	0.93[bc]	6.7	30.35
5	30 m_ Qmax _75%	58.3	61.1	1.03[b]	2.58	6.35
6	30m_ Qmax _100%	61.2	78.1	0.97[bc]	4.97	19.66
7	50 m_ Qmax _50%	51.0	54.4	0.82[c]	14.75	28.92
8	50 m_ Qmax _75%	65.0	84.4	1.37[a]	16.49	40.5
9	50m_ Qmax _100%	42.5	74.1	1.25[a]	11.46	26.8
Lsd (0.05)			0.19	0.19		
CV			14.8	14.8		

***Table 9.** Continued.*

No	Slope (%)	Furrow width (m)	Furrow length (m)	Discharge (lit/sec)	LY (ton/ha)	Seed yield (ton/ha)
1	0.53	0.9	10	0.8	5.48 [c]	3.56[c]
2	0.53	0.9	10	1.2	5.93[bc]	3.12[c]
3	0.53	0.9	10	1.6	6.21[abc]	3.45[c]
4	0.53	0.9	30	0.8	6.72[ab]	3.72[c]
5	0.53	0.9	30	1.2	6.86[a]	4.12[bc]
6	0.53	0.9	30	1.6	6.72[ab]	3.86[c]
7	0.53	0.9	50	0.8	6.47[ab]	3.32[c]
8	0.53	0.9	50	1.2	6.86[a]	5.51[a]
9	0.53	0.9	50	1.6	6.82 [a]	5.03[ab]
Lsd (0.05)					0.85	1.13
CV					11.3	24.4

DU= Water Distribution Uniformity (%), WP= Water productivity, AE= Application Efficiency, DU= Distribution Efficiency (%), $T_{0.5L}$= Advance time in minutes at the middle of the furrow length, T_L=Advance time in minutes at the end of the furrow length.

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