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PRINCIPLES AND DESIGN FOR FURROW IRRIGATION TO IMPROVE APPLICATION EFFICIENCY

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Abstract

Principle formulae based on many field trials were derived as a useful tool for designing the furrow irrigation system on calcareous sandy clay loam soil at North Western region of Egypt. The water application efficiency (E_a) can substantially be improved if proper combination of stream size, furrow slope, and length of run are adopted to the infiltration characteristics of the soil. According to the analysis presented herein, E_a achieved 70% under the limits to the variables usually practiced and subjected to increase if the surface runoff be collected in a waste ditch and reuse again. The surface runoff loss was 30% (on the average) under the limits of the variables used. A design example was presented to illustrate the applicability of the derived formulae.

Notations

A_s	apparent specific gravity of soil, dimensionless.
C	constant in the infiltration equation.
d	depth of irrigation water, cm.
D	accumulated infiltration depth, cm.
D_L	depth of water infiltrated at lower end of furrow, cm.
D_u	depth of water infiltrated at upper end of furrow, cm.
D_{root}	depth of effective root zone, cm.
E_a	application irrigation efficiency, %
K	Constant in water advance equation.
L	Length of water advance, m.
m	exponent in water advance equation.
n	exponent in the infiltration equation.
N	advance number, dimensionless.
P_1	essential deep percolation, %.
P_2	unessential deep percolation, %.
q	runoff stream size, m^3/min.
Q	irrigation stream size, m^3/min.
Q_e	maximum non-erosive stream size, m^3/min.
S	slope of the furrow, per cent.
t	time of advance, min.
T_f	time required for water to reach the end of the furrow, min.
T_r	time required to supply the root zone by the depth of irrigation water (d), min.
θ_{10}	soil water content (%) at 10 KPa suction.
θ_{1000}	soil water content (%) at 1000 KPa suction.

1. Introduction

Furrow irrigation is widely practiced in Egypt, even in the new reclaimed areas. It has been observed that more than one third millions feddans of highly calcareous soils in the North Western region of Egypt are subjected to furrow irrigation system. To design a suitable furrow irrigation system, knowledge of field characteristics and of the water delivery system is necessary. The most important variables affecting the application efficiency are infiltration characteristics of the soil, slope of the furrow, and the stream size used. Low application efficiency in furrow irrigation have generally attributed to the deep percolation losses below the root zone and surface runoff [1].

Numerical method for estimating the advance of water was presented by Davis [2]. Philip and Farrell [3], using the Laplace transformation, presented a detailed derivation of a general solution to the Lewis-Milne infiltration-advance equation. However, their solution required the use of real and complex parameters and the use of the error function. The relationships between the rate of advance and the infiltration rate of soil were discussed [4,5].

Criddle et al. [6] suggested that the furrow stream should reach the end of the run in one-fourth the time required to refill the root zone. However, this fourth-rule can not be applied to all the soils. El-Shafei [7], through an extensive study of infiltration in calcareous soils, found that the infiltration rate of the irrigated soil can well be expressed by exponential type equation. An analysis based on Euler's Beta function for evaluation of advance of water in furrow irrigation was presented [8].

The objective of this paper was to find out through field experiments, the appropriate design of furrow-irrigation taking into consideration the most influencing factors, stream size (Q), length of run (L), furrow slope (S) and infiltration characteristics of the soil.

2. Experimental Procedure

Field trials on many furrows were carried out at Burg El-Arab area, North Western region of Egypt. Three stream sizes (Q); 0.12, 0.18 and 0.29 m^3/min combined with three furrow slopes (S); 0.10, 0.20 and 0.60 were adopted. Each furrow was 200 m long with 80 cm spacing. The time of water advance was recorded at stations 20 m apart along the furrow. The total time of irrigation (T_t) per each run was estimated as $T_t = T_f + T_r$.

T_f = time required for water to reach the end of the furrow.
T_r = time required to supply the root zone by the desired depth of irrigation water, d [7].

$$d = 0.50 \left(\frac{\theta_{10} - \theta_{1000}}{100} \right) \times A_s \times D_{root} \tag{1}$$

where, θ_{10} and θ_{1000} are soil water retention (weight basis) at 10 and 1000 KPa suction respectively, A_s is the apparent specific gravity of the soil, and D_{root} equals the depth of the effective root zone. The effective root depth for most of the plants cultivated in the area is considered 30 cm on the average.

The soil was classified as calcareous sandy clay loam (25% clay, 20% silt and 55% sand) with 35% total calcium carbonates on average. The average apparent specific gravity (A_s) of the soil up to one meter depth was 1.40. The water retention at 10 and 1000 KPa suction in composite disturbed samples was 24.1% and 9.8% on dry weight basis, respectively.

If the value of (d) be introduced in the infiltration equation of the soil, the time (T_r) can be determined. Five infiltration tests were carried out by double cylinders infiltrometers at different sites in the field. All the infiltration data were plotted on Logarithmic scale and the infiltration equation of the soil was derived by regression as:

$$D = CT^n \tag{2}$$

where, D = accumulated infiltration depth, cm.

T = time, min.

n = positive exponent, depending on soil type(from 0.1 to 1.0)

The water was issued from an equilizing ditch to the head of the furrow through a small parshal flume weir (Fig. 1). Three furrows were designated to each treatment such that the measurement was always recorded on the middle one. A waste ditch was performed at the end of the furrows to collect the runoff water (Tail water). The runoff stream (q) was measured volumetrically at three different times, at the beginning of runoff, middle and near the end of the irrigation period. This makes the runoff estimation more accurate instead of depending on one measurement and using it as a constant rate of runoff.

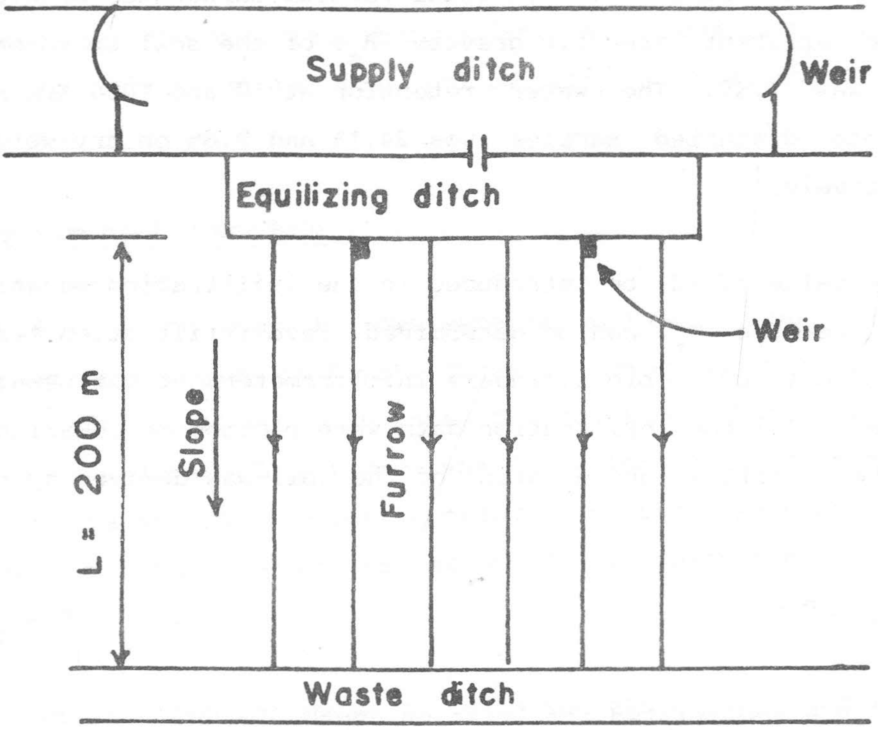


Fig.1. SCHEMATIC DIAGRAM FOR WATER MEASUREMENT IN THE FIELD.

3. Results and Discussion

The appropriate depth of irrigation water (d) is estimated by the proposed equation (1).

$$d = 0.50 \left(\frac{14.3}{100} \right) \times 1.4 \times 30 = 3.0 \text{ cm.} \tag{1}$$

The experimental infiltration data (Fig. 2) produced a good fitting by equation (2) with correlation coefficient equals 0.965. The regressed accumulated infiltration depth (D-cm) as a function of time (T-min.) is:

$$D = 0.32\, T^{0.51} \tag{2}$$

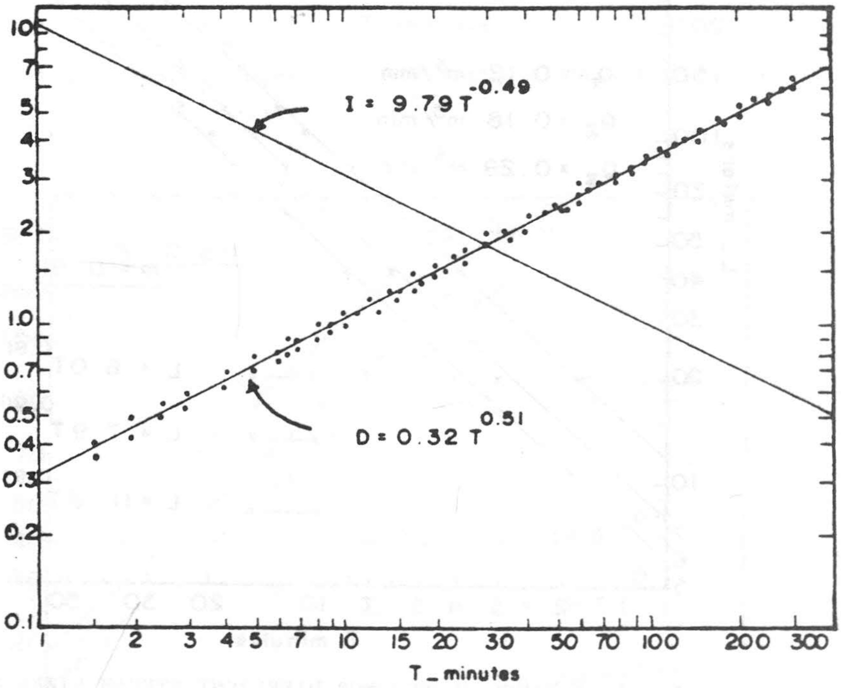


Fig.2. THE REGRESSED ACCUMULATED INFILTRATION DEPTH (D) AND INFILTRATION RATE (I) OF THE CALCAREOUS SOIL.

consequently, the constants C and n are equal to 0.32 and 0.51, respectively for the calcareous soil. Equations (1) and (2) are used conjugately for estimating the time (T_r).

$$3.0 = 0.32\ T_r^{0.51} \quad , \text{ and } T_r = 80 \text{ min.}$$

The time (T_f) is actually dependent on stream size (Q), slope of furrow (S), and the length of run (L). Figures (3,4 and 5) present the

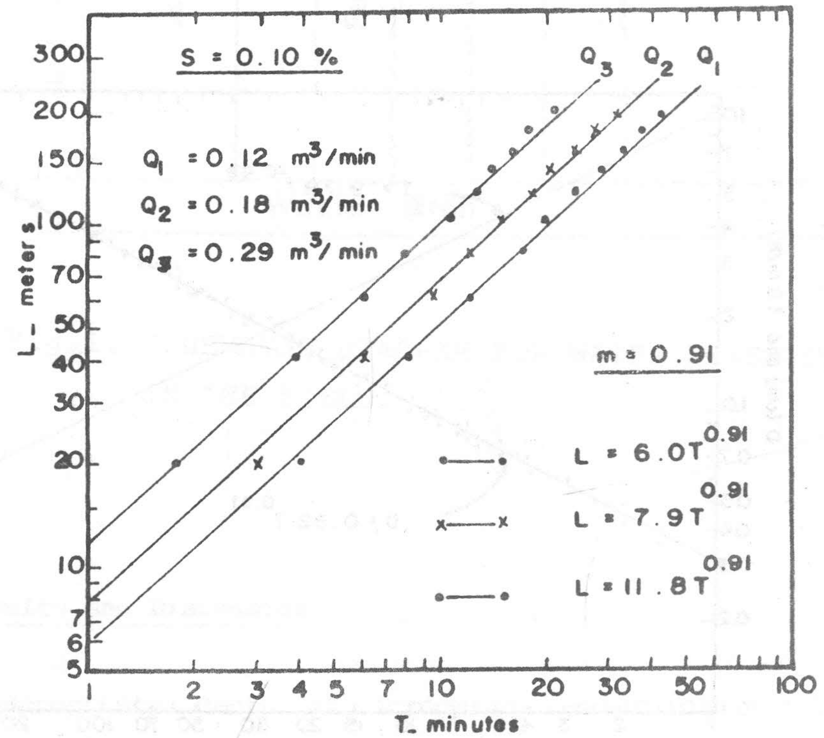


Fig.3. ADVANCE CURVES FOR DIFFERENT STREAM SIZES UNDER SLOPE 0.10%.

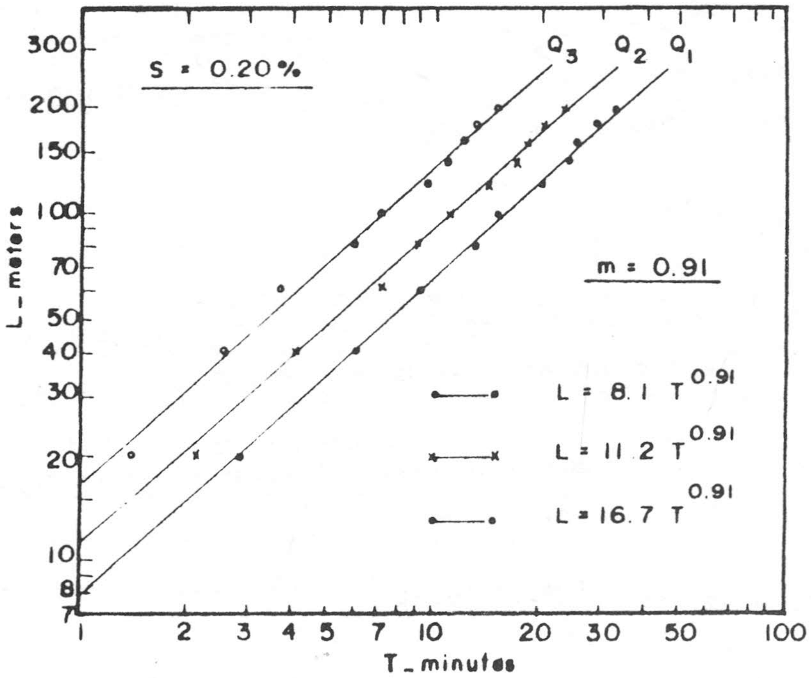


Fig.4. ADVANCE CURVES FOR DIFFERENT STREAM SIZES UNDER SLOPE 0.20%.

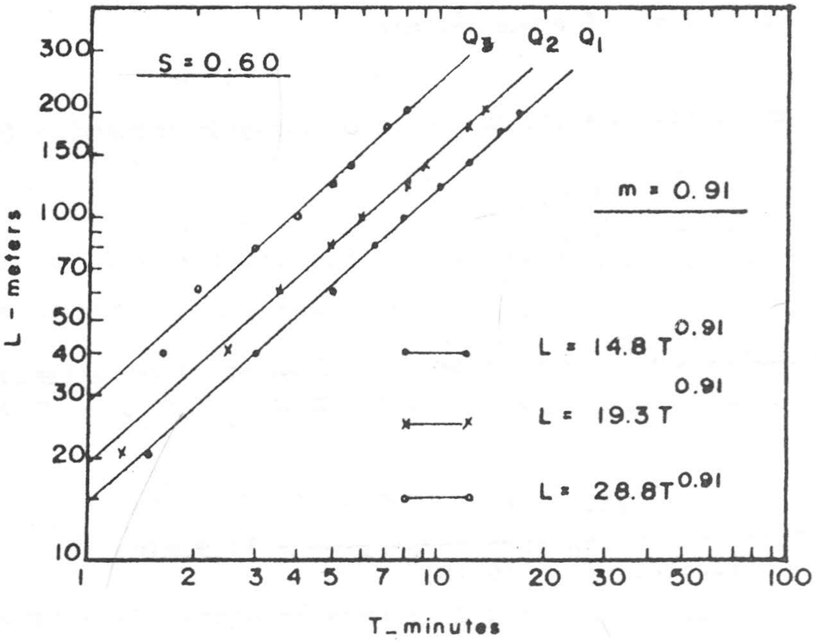


Fig.5. ADVANCE CURVES FOR DIFFERENT STREAM SIZES UNDER SLOPE 0.60%.

advance of water in the furrows under the different values of Q and S. The results indicate that the advance of water can really be expressed by the exponential equation (3).

$$L = Kt^{m} \tag{3}$$

Where, m = a constant equals 0.91 for the calcareous soil.
K = a constant depends on Q and S.

Through the complete analysis of advance curves in Figures (3,4, and 5), the equation (4) was derived.

$$L = 97\ S^{0.50}\ Q^{0.77}\ t^{0.91} \tag{4}$$

Where, L = length of water advance, m.
S = slope of the furrow, per cent.
Q = stream size, m^3/min.
t = time of advance, min.

The time of advance (t) can also be given by equation (5).

$$t = \frac{L^{1.10}}{153.3\ S^{0.55}\ Q^{0.85}} \tag{5}$$

For instant, the advance time (t) of water along a length of run (L) = 135 m, with S = 0.20 and by Q = 0.18 m^3/min. is:

$$t = \frac{(135)^{1.1}}{153.3(0.20)^{0.55}(0.18)^{0.85}} = 14.9 \text{ min.}$$

which coincides with the value 15 min. (Fig.4). Equation (5) can now predit the time (T_f) for any combination of stream size (Q), furrow slope (S), and any length of run (L) with the limits of the imposed variables.

The total time of irrigation (T_t) is essentially equal to $(T_f+T_r) = (T_f + 80)$ min. In other words, the advancing water in the furrow will reach the end by time (T_f), then irrigation is continuing for time (T_r) to supply the root zone by water depth (d). Since T_f is a fraction of T_r (Table 1), deep percolation (P) below the root zone will take place after a period of time longer than T_f. Deep percolation can be classified to essential (P_1) which is unavoidable and unessential (P_2) which can be avoidable by proper design (Fig. 6). P_1 is indispensably taken place to provide the lower end of the furrow with the irrigation depth (d). However, P_2 is taking place due to the overirrigation which should be prevented by the designer by limiting the irrigation period to only $(T_f + T_r)$. By introducing the advance number (N) as:

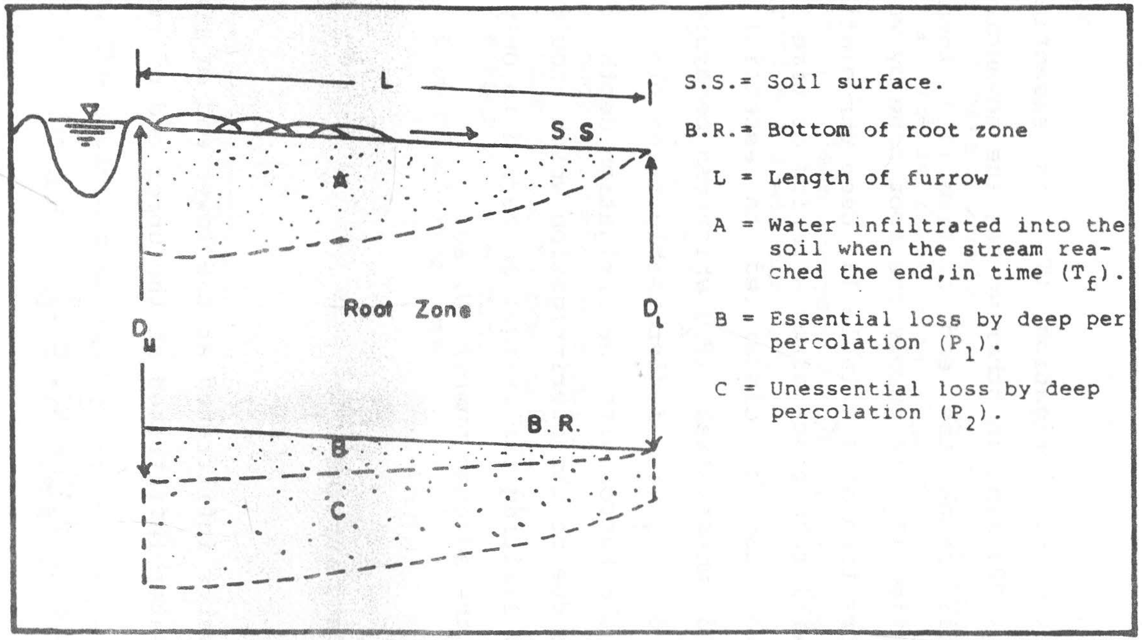
$$N = \frac{T_r}{T_f}$$, and letting :

D_L = depth of water infiltrated at the lower end of run, cm.,
D_u = depth of water infiltrated at the upper end of run, cm.

$$D_L = C\ T_r^n = C\ (N\ T_f)^n = N^n .\ C\ T_f^n \qquad (6)$$

$$D_u = C(T_r + T_f)^n = C(N\ T_f + T_f)^n = (N+1)^n . C\ T_f^n \qquad (7)$$

By considering the shape of essential percolation loss (P_1) beneath



S.S.= Soil surface.

B.R.= Bottom of root zone

L = Length of furrow

A = Water infiltrated into the soil when the stream reached the end, in time (T_f).

B = Essential loss by deep per percolation (P_1).

C = Unessential loss by deep percolation (P_2).

Fig. 6. SCHEMATIC DIAGRAM USED IN THE ANALYSIS OF FURROW IRRIGATION DESIGN.

the root zone as triangular pattern, which is very close in reality (Fig. 6), P_1 can be determined as percentage by equation (8).

$$P_1 = \frac{(D_u - D_L).\ L/2}{(D_u + D_L).\ L/2} \quad \text{(per unit width)}$$

$$P_1 = \frac{(N+1)^n - N^n}{(N+1)^n + N^n} \times 100 \qquad (8)$$

Table (1) presents the calculated (P_1) for three values of Q, S and L. Table (1) reveals that P_1 could vary from 1 to 11 % as the advance number (N) been reduced from 20 to 2. It is known that longer length of run means more elimination of additional structures, cross ditches and additional setting, thus reducing cost and labor of the irrigation. However from practical point of view, the design of furrow irrigation necessitates proper compromise between low percolation losses on one hand and reduced additional structures and operation costs on the other hand, in addition to other important considerations such as erosion, available stream size, original land slope and surface runoff. For example, one can obtain low value of P_1 (around 2%) under large stream size (Q_3), but severe erosion will be occured. The following empirical relationship is proposed here to be used as a guide for determining the maximum non-erosive stream size (Q_e) for the calcareous soil.

$$Q_e = \frac{0.05}{\text{per cent slope}} = m^3/\text{min} \qquad (9)$$

Practically, the design which leads to P_1 up to 10 % without serious erosion should be accepted. This can be achieved by different layouts as can be detected from Table (1).

Surface runoff (q) is very important in determining the overall application efficiency (E_a). Surface runoff is taking place during a time period equals to T_r. The application efficiency can greatly be increased if the surface runoff can be collected in a waste ditch as tail water and reused again. In this investigation, E_a will be determined by considering the surface runoff as losses to give some lights about the percentage of runoff under furrow system.

Table (1) **Percentage of essential deep percolation (P_1) for different values of stream size (Q), furrow slope (S), and length of run (L).**

L = 200 m									
S	0.10			0.20			0.60		
Q(m^3/min)	0.12	0.18	0.29	0.12	0.18	0.29	0.12	0.18	0.29
T_f (min)	42	32	21	34	24	15	17	13*	8**
N	1.9	2.5	3.8	2.4	3.3	5.3	4.7	6.2	10
P_1	10.8	8.6	5.9	9.0	6.6	4.5	5.0	3.8	2.4
L = 150 m									
T_f (min)	32	24	15	25	17	11	13	10	6
N	2.5	3.3	5.3	3.2	4.7	7.3	6.2	8	13.3
P_1	8.6	6.6	4.5	6.9	5.0	3.2	3.8	3.0	1.8
L = 100 m									
T_f (min)	20	15	10	15	11	7	8	6	4
N	4	5.3	8	5.3	7.3	11.4	10	13.3	20
P_1	5.6	4.5	3.0	4.5	3.2	2.1	2.4	1.8	1.2

* moderate erosion

** severe erosion

lights about the percentage of runoff under furrow system.

E_a = (water stored in root zone/water applied) x 100

$$E_a = \left[1 - \left(\frac{T_r}{T_r + T_f} \right) \left(\frac{q}{Q} \right) - P_1 \right] 100 \qquad (10)$$

Where, q = runoff stream size (outflow), m^3/min.

The following example will be drawn to illustrate the use of equation (10):

$$S = 0.20,\ Q = 0.12\ m^3/min.,\quad q = 0.032\ m^3/min.$$

$$L = 200\ m,\ T_r = 80\ min.,\quad T_f = 34\ min.\ \text{(Table 1)}$$

$$E_a = \left[1 - \left(\frac{80}{114} \right) \left(\frac{0.032}{0.12} \right) - 0.09 \right] \times 100 = 72.3\%$$

Table(2) Application efficiency (%) under different furrow slopes and stream sizes for a length of run = 200 m.

S	$Q_1 = 0.12$			$Q_2 = 0.18$			$Q_3 = 0.29$		
	q	q/Q	E_a	q	q/Q	E_a	q	q/Q	E_a
0.10	0.030	0.25	72.8	0.048	0.27	72.4	0.088	0.30	70.1
0.20	0.032	0.27	72.3	0.053	0.29	70.7	0.093	0.32	68.5
0.60	0.035	0.29	71.0	0.055	0.31	69.9	0.098	0.34	66.8

* Q and q (m^3/min).

Table (2) summerizes the estimation of E_a for length of run equals 200 m under the different slopes and stream sizes. It can be concluded from Table 2 that proper design for furrow irrigation yields an application efficiency 70% with 30% runoff on the average, and this high value of E_a can be attained under a wide variety of slope and stream size. It is worthy of mentioning here that E_a which usually determined in our fields is below 55%. This is attributed mainly to the unessential deep percolation (P_2) due to the overrrigation as result of inefficient design of the system.

Finally, all the equations derived and analyses presented herein will be implemented conjugately in the following design example to illustrate its applicability.

Design Example

Calcareous sandy clay loam soil

Available stream size = 0.20 m^3/min.

Accordingly

Depth of irrigation water (d) = 3.0 cm. (Equation 1)

Time required to irrigate the root zone (T_r) = 80 min (Equation 2)

$$\text{maximum allowable slope (S)} = \frac{0.05}{0.20} = 0.25 \qquad \text{(Equation 9)}$$

The advance number (N) which produces unavoidable deep percolation (P_1) not more than 5% is :

$$5 = \frac{(N+1)^{0.51} - N^{0.51}}{(N+1)^{0.51} + N^{0.51}} \times 100 \qquad \text{(Equation 8)}$$

$N = 4.7$

Time required for the advancing water to reach end of run (T_f):

$$T_f = \frac{T_r}{N} = \frac{80}{4.7} = 17 \text{ min.}$$

The proper length of furrow (L) is :

$$L = 97\,(0.25)^{0.50}\,(0.20)^{0.77}\,(17)^{0.91} = 185 \text{ m. (equation 4)}$$

The value of T_f can be confirmed now by introducing L = 185 m into equation (5):

$$t = \frac{(185)^{1.10}}{153.3(0.25)^{0.55}\,(0.20)^{0.85}} = 17.1 \text{ min.} = T_f \qquad \text{(equation 5)}$$

The expected water application efficiency (E_a):

$$E_a = \left[1 - \left(\frac{80}{97}\right)(0.30) - 0.05\right] \times 100 = 70.2\ \% \qquad \text{(equation 10)}$$

So, the appropriate design should imply $Q = 0.20\ m^3$/min., S = 0.25 , and L = 185 m which can produce E_a = 70% with the consideration of 30% surface runoff. E_a will greatly increase if the surface runoff can be collected and reuse again.

4. Conclusion

The water application efficiency on furrow irrigation system can be increased if the following factors are considered in the design:

Stream size, furrow slope, length of run, infiltration rate of the soil, and the effective root zone.

Both the total amount of water applied and the amount of deep percolation can be reduced by implementing those factors conjugately.

Formulae for predicting the water advance rate, the non-erosive stream size and expected water application efficiency were derived to be applicable on calcareous sandy clay loam soils which are prevailing at North Western region of Egypt. The research, however, does provide important insights and guidlines to water management under furrow irrigation system.

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