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Water Use Efficiency in a Furrow System

T.S. Lee[1] and H.O. Balla[2]

[1]*Department of Field Engineering*
Faculty of Engineering
Universiti Pertanian Malaysia
43400 Serdang, Selangor, Malaysia

[2]*Assistant Divisional Engineer*
Gezira Irrigation Scheme
Sudan

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ABSTRAK

Satu pendekatan perseimbangan isi padu berserta persamaan Kostiakov untuk menilai parameter-parameter penyusupan tanah dalam furrow dipergunakan. Parameter lain yang mustahak merangkumi parameter geometri furrow, anggapan profil air di bawah tanah dan data mara aliran. Satu set furrow berdekatan boleh diuji kaji untuk menghasilkan nilai prestasi sistem furrow. Pendekatan yang dihuraikan di sini boleh digunakan untuk menilai kecekapan pengairan furrow mod berterusan. Variasi ciri-ciri penyusupan dari segi lokasi dan masa sudah dikenali. Oleh itu, prestasi sistem pengairan furrow yang menggunakan permukaan tanah sebagai bahantara membawa air akan bertukar-tukaran bersama-sama penyusupan yang sentiasa bertukar. Jadi, satu prosedur penilaian yang boleh diguna sepanjang musim pengairan diperlukan untuk membenarkan pertukaran pengairan dibuat. Penentuan perlakuan pengairan ini tertakluk kepada penilaian proses penyusupan yang tepat, yang mana dalam kes ini, aliran air permukaan semasa penyusupan dalam saluran kecil adalah dinamik. Satu contoh penilaian diberi.

ABSTRACT

An existing volumetric balance approach in conjunction with the Kostiakov infiltration equation for determining soil infiltration parameters in a furrow is used to study furrow irrigation in the local environment. Other parameters required include furrow geometry, assumed subsurface profile and flow advance data. A set of adjacent furrows is used to indicate the performance of the field system. The procedure outlined here can be used to evaluate efficiency of continuous mode furrow irrigation. The spatial and temporal variation of infiltration characteristics of a soil are well known. As such, the performance of a furrow irrigation system which uses the soil as a medium of conveyance varies with the ever-changing infiltration behaviour. There is therefore a need for an evaluation procedure to determine water use efficiency which can be followed throughout the irrigation season so as to enable the irrigator to make any necessary changes to improve its performance. This determination of irrigation performance hinges very much on the correct evaluation of the infiltration process, in this case, in dynamic infiltration water flowing overland in small channels. An evaluation example is given.

Keywords: furrow, infiltration, irrigation efficiency

INTRODUCTION

The objective of any irrigation system is to replenish the soil to a suitable moisture level at any time for healthy plant growth. The amount required depends on the management allowable deficit of the available water between field capacity and permanent wilting point, taking into consideration the root depth at the stage of plant growth considered. Infiltration is the movement of water through the soil. As the capillary pores at the surface are filled and intake capacity is reduced, the infiltration rate gradually decreases until the zone of aeration is saturated. The factors affecting infiltration are quite well known. The system is said to be performing at optimum, that is at high application efficiency, when the required level of moisture is maintained while surface runoff losses and deep percolation are minimized. However, furrow irrigation is often characterized by low efficiency, either due to unskilful management and operation or from poor design. Since infiltration is always at a minimum at the furrow's lower end, this end is generally planned to receive the design water requirement. However, in many situations under continuous irrigation, to achieve this design requirement means that in furrows with fast advance there would be tremendous loss of water due to runoff at the lower end and deep percolation at the top end of the furrow. On the other hand, in adjacent furrows there may be cases where furrow flows hardly reach the end, thus under-irrigating these furrows.

This phenomenon in furrow irrigation is due to temporal and spatial variation of the infiltration characteristics in a furrow. In view of this, the operation of a furrow system would require that the performance of a trial set of furrows be evaluated. This is particularly important when water supply is limited. The assessment is based on measurements taken in the field under the conditions and practices followed. Modifications to improve the system can then be made. Careful management is essential for a stable and efficient agriculture. Realistic planning of water management and conservation activities requires accurate information on the rate at which various soils take in water under different conditions.

It has been shown (Woon 1987) that for a particular soil type, infiltration depends on the number of wetting runs, day of wetting and obvious decreases with time. For example, for one wetting run per day of

150-mm depth of water, the total time needed to completely infiltrate a sandy soil is less than five consecutive wetting runs of 30-mm depth. This phenomenon is due to surface sealing, when a wetted soil is exposed to the atmosphere prior to being wetted again. This phenomenon is more evident in loamy soil than in sandy soil and is an important aspect that has to be taken account of in infiltration studies.

The objective of this paper is to evaluate the infiltration in a furrow system using an existing method in order to evaluate its usefulness in the local context and to outline a semi-empirical procedure to carry out an evaluation of the water use efficiency in a furrow irrigation event.

METHODOLOGY

The evaluation of the infiltration characteristics in a furrow where dynamic water flow occurs is difficult. The unsteady non-uniform flow makes such evaluation complicated. Factors such as furrow geometry, surface roughness and texture affects the infiltration rate. The double ring infiltrometer has been used for such evaluation (Balla 1991), but such isolated ponded infiltration does not adequately describe the infiltration behaviour in a furrow.

The assumptions (Lee 1982) made in this evaluation are:

1. The infiltration rate throughout the whole length of the furrow is the same, and is described by the Kostiakov equation.
2. The geometry of the furrow remains unchanged throughout the furrow.
3. Infiltration in a furrow is assumed to occur over the entire space between adjacent furrows.
4. The long-time basic infiltration rate over the length of furrow is constant.

Under field conditions, the trajectory of the advance of the water front can be described as the simple power function in light to medium soils (equation 1, from which equation 2 can be derived).

$$X = pt^r \tag{1}$$

$$r = \frac{Ln\frac{X_2}{X_1}}{Ln\frac{T_2}{T_1}} \tag{2}$$

$$z = k\tau^a + f_0\tau \tag{3}$$

It has been found that the Kostiakov equation incorporating an additional term for the final infiltration rate (equation 3) is highly effective in stimulating infiltrated volumes where reliable estimates of steady infiltration rate can be obtained (Walker and Skogerboe 1987). However, it was found (Hong 1990; Satifah 1991) that this procedure does not give good estimates in cases where water flow is fast. In such cases, the values of the soil infiltration can be erroneous. For such linear time advance flows, for example in heavy soils, the infiltration rate established from the inflow and outflow method is more realistic. However, more field trials need to be carried out to confirm this.

For evaluation of the extended Kostiakov soil infiltration, the two-point volume balance or conservation method in equation 4 (Elliot and Walker 1982) requires the volumes of inflows, basic rate infiltration, surface water volumes be evaluated at two points of advance (T_1, X_1) and (T_2, X_2) with Equation 2.

$$Q_0 t = \sigma_y A_0 X + \sigma_z k T^a X + \frac{w f_0 T X}{1 + r} \tag{4}$$

The inlet flow area can be derived from Manning's equation and furrow section properties, and is given by

$$A_0 = C_1 \left\{ \frac{Q_0 n}{60\sqrt{S_0}} \right\}^{C_2} \tag{5}$$

where the coefficients are given as follows:

$$C_2 = \frac{3\sigma_2}{5\sigma_2 - 2\lambda_2} \tag{6}$$

$$C_1 = \sigma_1 \left\{ \frac{\lambda_1{}^{0.67}}{\sigma_1{}^{1.67}} \right\}^{C_2} \tag{7}$$

For the furrow geometry, the areas of cross-section and wetted perimeter is given by equations 8 and 9 respectively with **y** as depth of furrow.

$$Q = \sigma_1 y^{\sigma_2} \tag{8}$$

$$WP = \lambda_1 y^{\lambda_2} \tag{9}$$

To evaluate the coefficients, a logarithmic approach with section parameters at two chosen arbitrary depths of the measured furrow sectional profile is followed (see example in Appendix).

The basic (or final) infiltration rate is given by equation 10, that is,

$$f_0 = \frac{(Q_0 - Q_{out})0.06}{wX} \tag{10}$$

Two equations from equation 4 can be written (for the two points of advance) where equation 11 (that is the volumes of water infiltrated) is used and solved logarithmically (equation 12, assuming the end and middle times and distance are used) for a value of **a**. Then the value of $\boldsymbol{\sigma_z}$, the Kiefer Correction factor (equation 13) is calculated and both these are subsequently used in either of the two equations form with equation 11 to evaluate **k**.

$$V_x = \sigma_z k[T_x]^a X \tag{11}$$

$$a = \frac{\ln\left\{\frac{V_x}{V_{0.5x}}\right\}}{\ln\left\{\frac{Tx}{T_{0.5X}}\right\}} \tag{12}$$

$$\sigma_z = \frac{a + (1-a)r + 1}{(1+r)(1+a)} \tag{13}$$

With the establishment of the soil parameters **a** and **k**, the depths of infiltration at any point can be evaluated. The equations relevant for the infiltration characteristics of a furrow irrigation event is illustrated for the case where power time advance features are indicated. This semi empirical procedure is outline in the Appendix.

RESULTS AND DISCUSSION

Having evaluated the infiltration function in each of the furrow by following the procedure described, the depths of water infiltration for the predetermined sites along the furrow can be evaluated. The average infiltration depth in the furrows across the field is calculated at a particular section across the field. *Fig. 1* and *2* show the actual field water distribution derived from the infiltration function. The average infiltrated depth can be plotted into a water distribution profile. This can then be nondimensionalized simply by dividing each depth by the average depth and the distribution is plotted as in *Fig. 3*. In this figure, f_2 fraction of the total area would have received a depth of water h_{f2} or greater and (f_2 - f_1) fraction of the area would have received a water depth of between h_{f1} and h_{f2}.

From *Fig. 1*, *2* and *3*, we can evaluate the various category of volumes (nondimensional volume = nondimensional area times nondimensional depth) of water by measuring (with the aid of a planimeter) or calculating the areas of the sections in the figure.

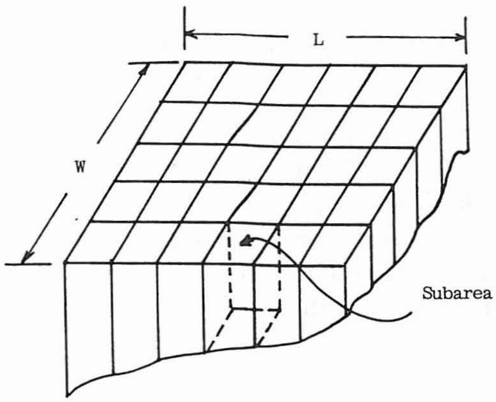

Fig. 1. *Depth of infiltrated water over an irrigated area with a set of furrows*

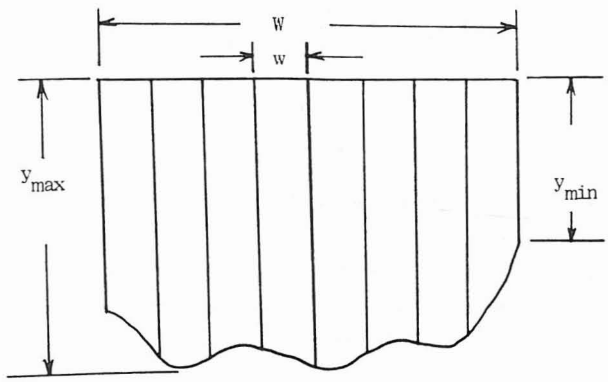

Fig. 2. *Depth of infiltrated water along a section across the furrow field*

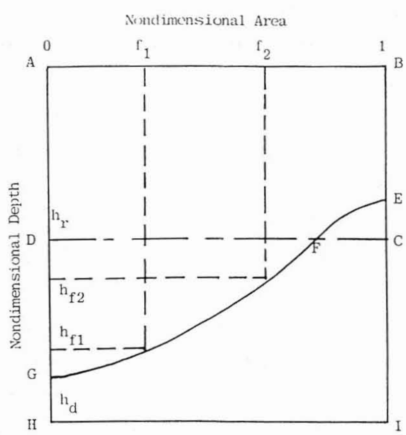

Fig. 3. *Averaged water distribution profile over an irrigated furrow field*

Thus from *Fig. 3*, we have the following:

a) Volume 1: The total infiltrated volume per unit width is given by the area bounded by ABEG.
b) Volume 2: The total volume of deep percolation losses per unit width is given by the area bounded by DFG.
c) Volume 3: The total volume of irrigation deficit per unit width is given by the area bounded by CEF.
d) Volume 4: The total volume supplied per unit width is the area bounded by ABIH.
e) Volume 5: The total required irrigation volume is given by area ABCD.
f) Volume 6: The total applied water replenishing water management allowable deficit per unit width is ABEFD.
g) Volume 7: The total volume of runoff losses per unit width is given by GHIE.

The efficiencies of water use, water runoff, water percolated ecetera can be calculated from the ratios of these volumes. An example for a single furrow system is given in the Appendix. For a set of furrows, the procedure is the same, except that an average condition is pursued.

CONCLUSION

The existing improved Kostiakov equation for determining the infiltration characteristics in a soil is found to be useful, in local situations, in furrow advance cases in which the rate of advance follows a power law. This equation however, is not useful in cases where the rate of advance is fast and follow a linear behaviour. An example of the former situation is furrows in sandy and sandy loam soils, while an example of the latter would be heavy soils such as clay and clayey loam soils. The performance of an irrigation event with a set of furrows can be illustrated with a water distribution profile over there area covered by a set of adjacent furrows. From this, the parameter for evaluating the trial irrigation event can be deduced to indicate the irrigation system efficiency, the deep percolation and runoff proportions. A quick assessment of a trial irrigation event from irrigation to irrigation or from season to season can be useful for managing such furrows systems efficiently.

The results obtained would only indicate the average condition for the set of furrows. The distribution pattern amongst the furrows is not evaluated. For furrows in which the lower reaches are not irrigated, the actual irrigation depth is zero. With more of these furrows not irrigated, the average depth for all furrows would be small. This, however, would not be indicative of those furrows that are adequately irrigated to the management allowable deficit. In order to improve the water distribution between furrows, either too much irrigation or not enough, the practice of surge flow (Walker and Skogerboe 1987) irrigation (which reduces the advance times as a result of reduced infiltration and volume required for advance, thus improving uniformity across the field) and/or cutback irrigation management is suggested for further research.

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APPENDIX

The following example shows the analysis for a set of six furrows under a continuous irrigation regime. An example of an evaluation for furrow 1 is given below to illustrate the evaluation procedure.The results of the other furrows are summarized in *Fig.4-9*. *Fig 10* shows the final averaged conditions for the whole set of furrows.

1. Field data (clay loam, UPM irrigation research site)

   Inflow Q_o = 0.094 m^3/min
   Outflow Q_{out} = 0.044 m^3/min
   Wetted perimeter (calculated from graph):
   $WP_{0.05}$ = 0.215 m
   $WP_{0.15}$ = 0.491 m

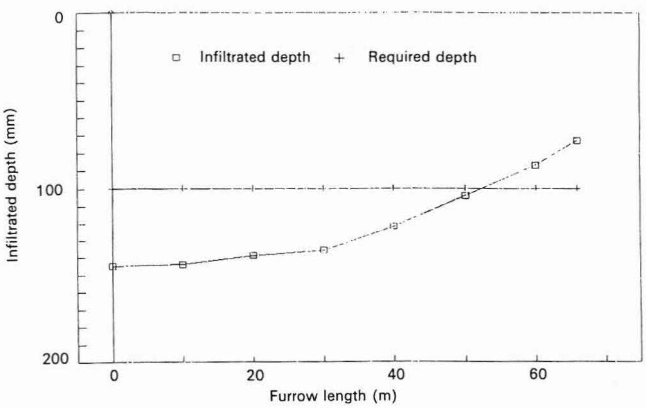

Fig. 4. Data for furrow 1

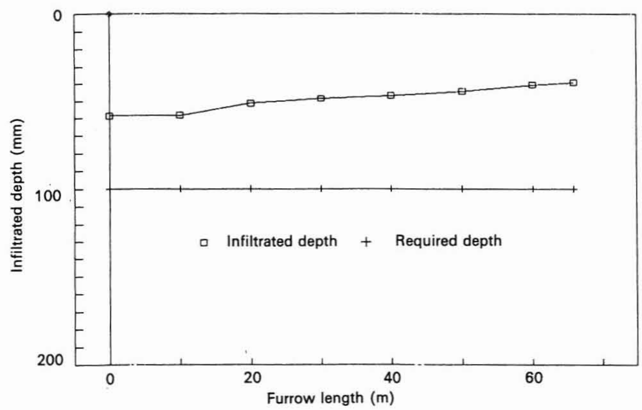

Fig. 5. Data for furrow 2

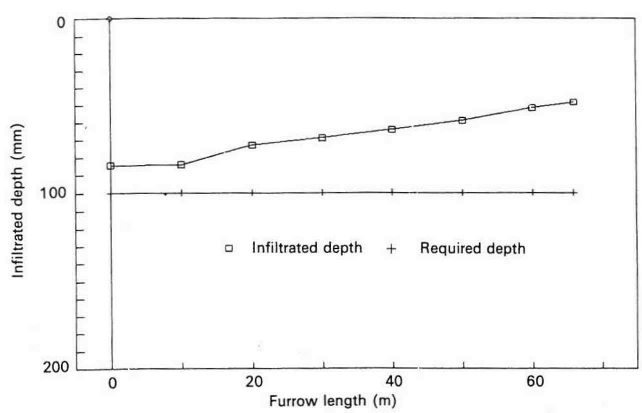

Fig. 6. Data for furrow 3

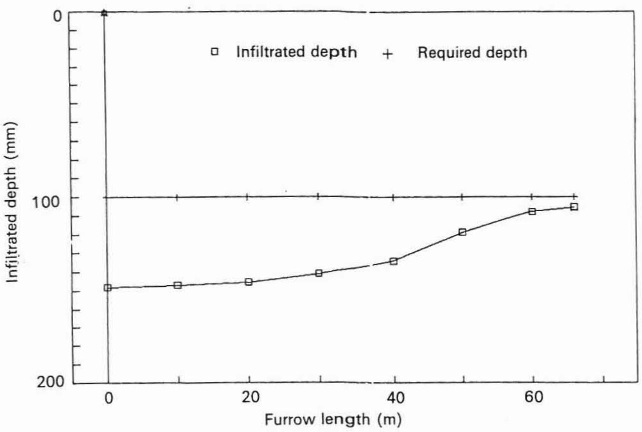

Fig. 7. Data for furrow 4

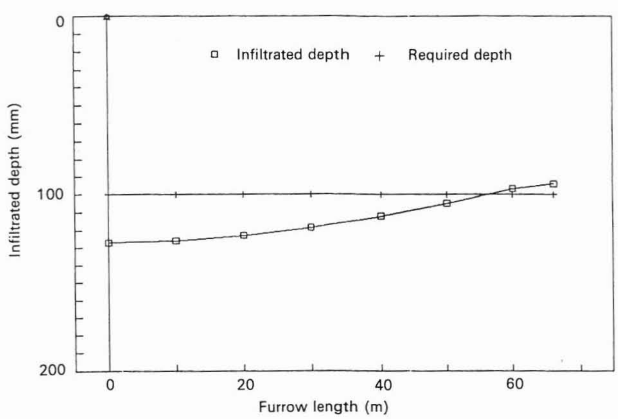

Fig. 8. Data for furrow 5

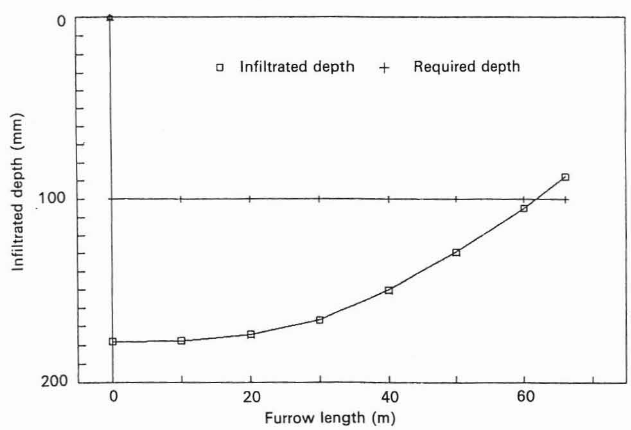

Fig. 9. Data for furrow 6

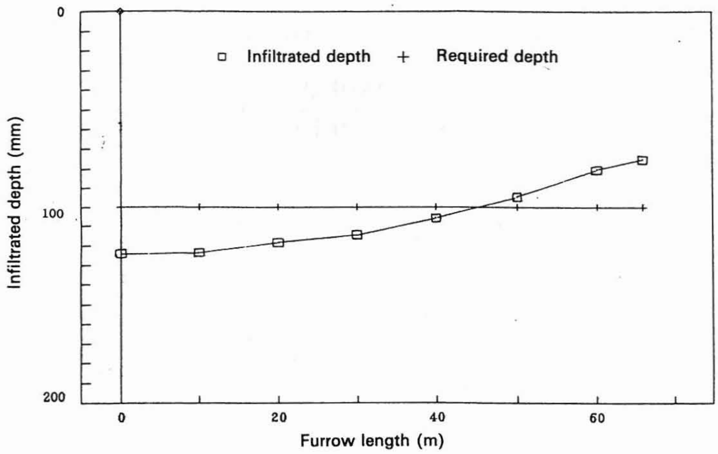

Fig. 10. Average infiltrated depth for furrow set

TABLE 1
Furrow section parameters

Depth of furrow (m)	Top width of furrow (m)
0.05	0.19
0.10	0.29
0.15	0.38
0.20	0.48

TABLE 2
Distances and times of flow advance

Distance X (m)	Time (min)
10	0.67
20	3.83
30	5.43
40	14.45
50	25.25
60	35.08
66	42.53

The top width of the furrow section at any furrow depth can be related to the depth by

$$TW = \alpha_1 y^{\alpha_2}$$

Using the logarithmic approach and the equation above, we have

$$\alpha_2 = \frac{\log(0.48/0.29)}{\log(0.20/0.10)} = 0.63$$

$$\alpha_1 = \frac{0.48}{(0.20)^{0.63}} = 1.26$$

$$\sigma_1 = \frac{\alpha_1}{\alpha_2 + 1} = \frac{1.26}{1.63} = 0.77$$

$$\sigma_2 = \alpha_2 + 1 = 1.63$$

From equation 9, the coefficients of the wetted perimeter equation are $\lambda_1 = 2.045$ and $\lambda_2 = 0.752$.

Hence coefficients of the area section equation are

$$C_1 = \frac{3\sigma_2}{5\sigma_2 - 2\lambda_2} = 0.736$$

$$C_1 = \sigma_1 \left\{ \frac{\lambda_1^{0.67}}{\sigma_1^{1.67}} \right\}^{c_2} = 1.51$$

and hence,

$$A_o = c_1 \left\{ \frac{q_o n}{60 S_o^{0.5}} \right\}^{c_2} = 0.00427\ m^2$$

Calculating r by the two points from the advance data, we have

$$r = \left\{ \frac{\log 2}{\log \frac{35.08}{5.43}} \right\} = 0.372$$

The basic infiltration rate is given by

$$f_o = \frac{0.094 - 0.044}{1 * 66} = 0.00076\ m^3/m/\text{min}$$

Forming two equations at the two points, with equation 11, we have

$$V_x = 0.033 \qquad V_{0.5X} = 0.0104$$

From Equation 12, the value of **a** is

$$\mathbf{a} = 0.561$$
$$\sigma_z = 0.81$$
$$\mathbf{k} = 0.00501$$

Thus the final infiltration equation for this furrow is

$$Z = 0.00501\ \tau^{0.561} + 0.00076\ \tau \quad m^3/\text{min}$$

The intake opportunity time and the infiltrated depths along the furrow are calculated with this equation and is shown in Table 3. The information for the other furrows is also included in Table 4.

TABLE 3
Calculated infiltration depths

Distance (m)	Intake opportunity time (min)	Infiltrated depth (mm)
0	71.15	145
10	70.48	144
20	67.32	139
30	65.72	136
40	56.72	122
50	45.90	104
60	36.07	87
66	28.62	73

TABLE 4
Infiltrated depths for the furrow set

Distance	Infiltration in Furrow Number (mm)						
(m)	1	2	3	4	5	6	Average
0	145	58	84	152	127	180	124
10	144	58	84	150	126	178	123
20	139	52	73	146	123	175	118
30	136	48	69	142	120	168	114
40	122	46	64	134	112	150	105
50	104	45	59	120	105	130	94
60	87	41	52	107	96	105	81
66	73	39	48	105	94	88	75

2. Furrow spacing w = 0.7 m
   Total furrow area = 323.4 m^2
   Table 5 shows the water distribution profile over the single furrow area.

TABLE 5
Water distribution profile

Non-dimensional area	Non-dimensional depth
0.00	1.24
0.15	1.23
0.30	1.18
0.45	1.14
0.60	1.05
0.76	0.94
0.91	0.81
1.00	0.75

Fig. 11 shows the plot of the water is required to be stored in the soil reservoir. The following efficiencies can be evaluated from *Fig. 11*.

Total infiltrated volume (ABEFG) = 1.021
Total volume of deep percolation (DFG) = 0.083
Total volume of irrigation deficit (ECF) = 0.038
Total volume of water supplied (ABIH) = 1.24
Total required soil water storage (ABCD) = 1.0
Total actual useful storage (ABEFD) = 0.937
Total volume of runoff losses (EIH) = 0.219

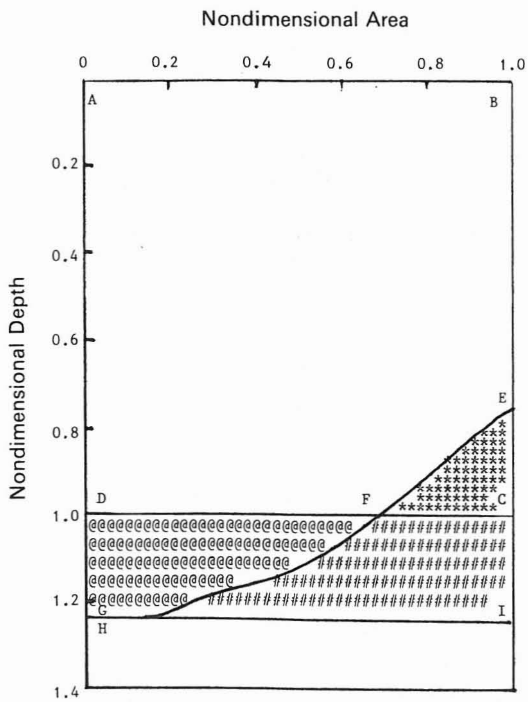

Fig. 11. Water distribution profile for the furrow set

$$\text{Water use efficiency} = \frac{0.937}{1.24} \times 100 = 75.6\%$$

$$\text{Water runoff losses} = \frac{0.219}{1.24} \times 100 = 17.7\%$$

$$\text{Deep water percolation} = \frac{0.083}{1.24} \times 100 = 6.7\%$$

$$\text{Soil reservoir storage} = \frac{0.937}{1.0} \times 100 = 93.7\%$$

LIST OF SYMBOLS

X	–	distance of flow advance
t	–	time of inlet discharge
WP	–	wetted perimeter
TW	–	furrow top width related to depth
τ	–	opportunity time for infiltration
r, p	–	coefficient of power advance equation
z	–	depth of infiltration
Z	–	infiltration
w	–	furrow spacing
a, k	–	soil coefficients of the infiltration equation
S_o	–	slope of furrow
f_o	–	final basic infiltration rate
Q_o	–	discharge into furrow
Q_{out}	–	discharge out of furrow
α_i	–	coefficients of furrow geometry
σ_i	–	coefficients of furrow geometry
λ_i	–	coefficients of furrow geometry
A_o	–	cross sectional area of flow
σ_z	–	subsurface infiltration shape factor
σ_y	–	surface flow shape factor
C_i	–	coefficients of furrow geometry
V_x	–	volume of infiltration
T_i	–	time of flow advance