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APPLICATION OF ON-FARM IRRIGATION EFFICIENCY APPROACH

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CONTENTS

INTRODUCTION

One of the most important terms that is used by irrigation specialists in designing and operating irrigation projects is irrigation efficiency. The calculation of surface irrigation efficiencies requires the determination of infiltrated water volume and water distribution profile. From the water distribution profile, one can directly derive the efficiencies.

The field irrigation is considered as a two dimensional process. Irrigation water is applied at the head of the field with a certain stream size and a wave front is moving across the field. During irrigation of level basin by surface methods, water infiltrates into the soil beginning with stations closest to the head of the field as the irrigation stream advances to the tail. Infiltration continues during ponding which follows advance until all water completely recess from the soil surface at all field stations. The total infiltration depth at a given station in the field depends on the infiltration opportunity time at that station.

ADVANCE FUNCTION

An advance function was derived by Boels 1986 to describe the wavefront movement. Two equations were developed to distinguish between cracking and non-cracking soils. It was assumed that in the case of cracking soils, cracks will be immediately filled with water after irrigation starts and before infiltration takes place.
The advance functions derived can be written in the form:

a. For non-cracking soils

$$t_x = \frac{5}{3}\,\frac{1}{I}\left(\frac{n}{\sqrt{S_o}}\right)^{3/5}\left[q_o^{3/5} - (q_o - I.x)^{3/5}\right] \qquad (1)$$

$$V_{t_x} = \frac{5}{3}\left(\frac{n}{\sqrt{S_o}}\right)^{3/5}\left[\frac{5}{8}\,\frac{1}{I}\cdot q_o^{8/5} - (q_o - I.x)^{3/5}\left(\frac{5}{8}\cdot\frac{1}{I}\cdot(q_o - I.x)\right)\right] \qquad (2)$$

b. For cracking soils

$$t_{x_c} = t_x + \frac{V_c}{I}\ln\frac{q_o}{q_o - I.x} \qquad (3)$$

$$V_{t_{xc}} = V_{t_x} + V_c\cdot\frac{q_o}{I}\cdot\ln\frac{q_o}{q_o - I.x} \qquad (4)$$

where:

t_x, t_{x_c} = advance time of the irrigation streams across a basin or furrow for non-cracking and cracking soils respectively

$V_{t_x}, V_{t_{xc}}$ = volume of water infiltrated per unit width for non-cracking and cracking soils respectively

q_o = net stream size applied per unit length (m^2/s)

I = infiltration rate (m/s)

n = Manning's coefficient

S_o = energy line slope

V_c = volume of cracks preceeding irrigation (m^3/m^3)

x = distance from the head of the field (m)

VERIFICATION OF IRRIGATION EFFICIENCY APPROACH

To validate the on-farm irrigation efficiency approach, two practical examples are used herein:

EXAMPLE 1:

Data from ten advance-recession tests for irrigation carried out on basin crops at Abu Raya, Kafr El Sheikh, Egypt were collected in Table 1 (EWUP Tech. Report No. 57). The infiltration functions for such typical field conditions during irrigation are:

- first irrigation cycle on wheat

$$y(t)=14.5\ t^{0.373} \qquad t \leq 61.1 \text{ min} \tag{5}$$

$$y(t)=32.2\ t^{0.179} \qquad t > 61.1 \text{ min} \tag{6}$$

- second irrigation cycle

$$y(t)= 6.4\ t^{0.441} \qquad t \leq 8.09 \text{ min} \tag{7}$$

$$y(t)= 7.2\ t^{0.384} \qquad t > 8.09 \text{ min} \tag{8}$$

the units of y(t) and t are mm and min, respectively.

Table 1. Advance-recession data for irrigation of basin crops at Abu Raya, Kafr El Sheikh, Egypt (EWUP report no. 57)

Advance recession test no.	Crop	Irrigation number	Field length (m)	Advance time t_a (min)	Infilration opportunity time to (min)		
					At the head	At the tail	Average for the field
1	wheat	1	90	190	265	75	186
2	wheat	1	75	230	400	170	301
3	wheat	1	75	225	315	90	227
4	wheat	1	45	198	327	129	256
5	wheat	2	45	98	390	292	342
6	wheat	2	130	93	375	282	328
7	broad-beans	1	65	99	369	45	227
8	broad-beans	2	65	80	85	140	106
9	wheat	1	75	82	120	50	101
10	wheat	1	70	125	175	50	122

Determination of Stream Size

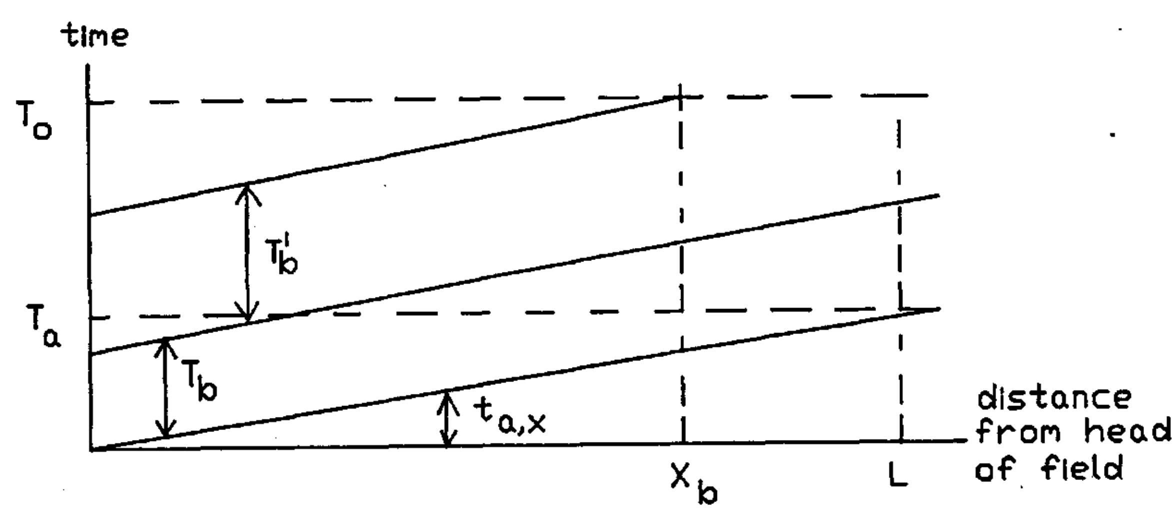


Fig. 1. Definition sketch

The total quantity of irrigation water supplied to the field plot per unit width is:

$$Q = \int_{0}^{X_b} a_2(T_o - \frac{T_a}{L} \cdot x)^{b_2}\, dx + \int_{X_b}^{L} a_1(T_o - \frac{T_a}{L} \cdot x)^{b_1}\, dx \qquad (9)$$

where:

T_o = infiltration opportunity time at the head of the field in min

T_a = advance time in min

L = plot length in m

a_1, b_1 = constants in infiltration functions 5 and 7 where $t \leq T_b$

a_2, b_2 = constants in infiltration functions 6 and 8 where $t > T_b$

$X_b \leq L$ where $X_b = \frac{T_o - T_b}{T_a} \cdot L$

If $X_b > L$, X_b is set equal to L

Integrating eq. 9 yields:

$$Q = \frac{a_2}{b_2 + 1} \cdot \frac{L}{T_a}[T_o^{b_2+1} - (T_o - \frac{T_a}{L} \cdot X_b)^{b_2+1}] +$$

$$\frac{a_1}{b_1 + 1} \cdot \frac{L}{T_a}[(T_o - \frac{T_a}{L} \cdot X_b)^{b_1+1} - (T_o - T_a)^{b_1+1}] \qquad (10)$$

The net stream size, q_o, expressed in $m^2.s^{-1}$ is calculated from:

$$q_o = \frac{Q}{T_a} \qquad (11)$$

Using the data shown in Table 1 and given by Kafr El Sheik team, the net stream size is calculated for each experiment. The results are shown in Table 2.

Determination of long-term infiltration rate

The cumulative infiltration function equals:

$$y(t) = a.t^b \tag{12}$$

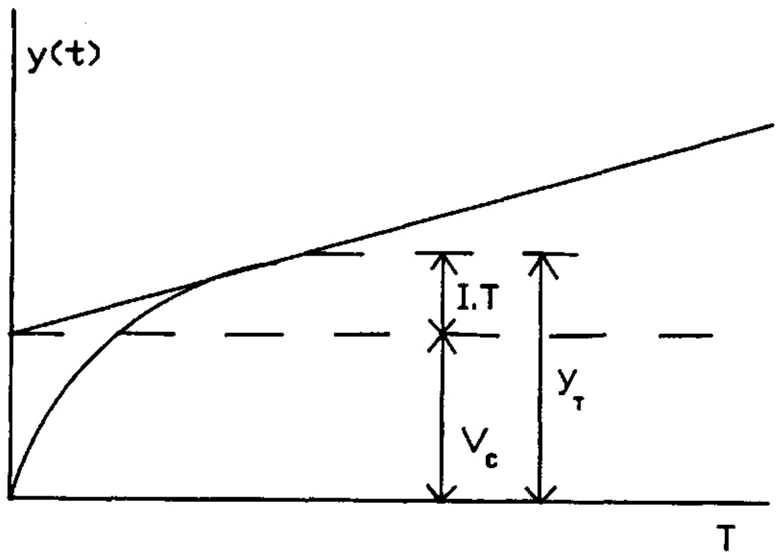


Fig. 2. Infiltration accumulation function

At some moments, T, a steady state condition is assumed (EWUP Tech. Rept. No.57). The infiltration rate I_t then equals:

$$I_t = \frac{d}{dt}[y(t)] = a \cdot b \cdot t^{b-1} \tag{13}$$

Using this rate as an invariable parameter, an initial crack volume is calculated from (Fig. 2):

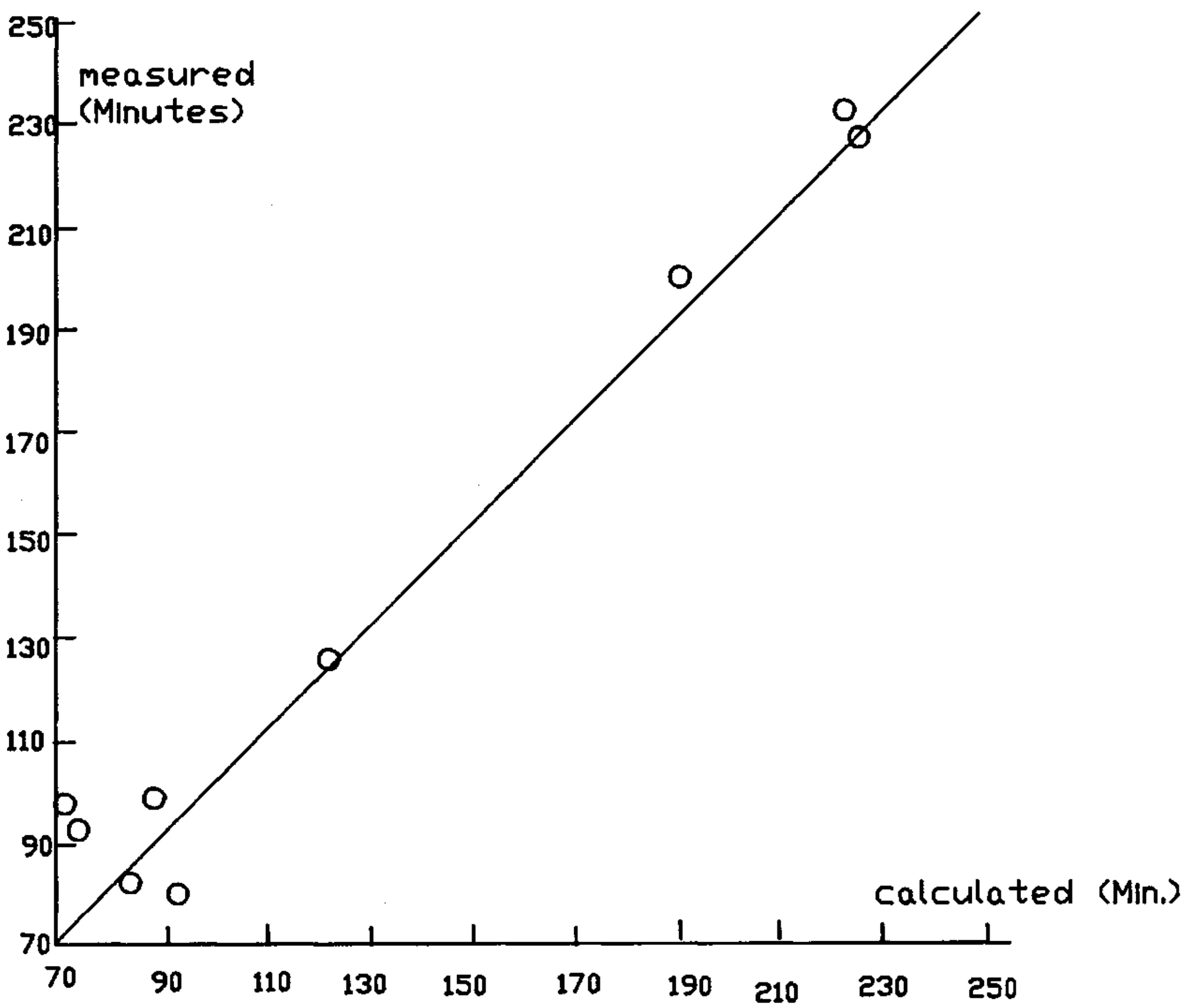
$$V_c = y_T - I \cdot T$$

$$= a \cdot T^b(1-b) \tag{14}$$

The long-term infiltration rate is evaluated at about 400 min. This results in:

$I = 0.0606\ m.d^{-1}$ and

$V_c = 0.0773\ m^3.m^{-2}$


250
measured
(Minutes)
230
210
190
170
150
130
110
90
70
calculated (Min.)
70
90
110
130
150
170
190
210
230
250

for the first irrigation and

$I = 0.0995 \ m.d^{-1}$ and

$V_c = 0.0443 \ m^3.m^{-2}$

for the second and subsequent irrigations on wheat.

The ratio $\left(\frac{n}{\sqrt{S_o}}\right)^{3/5}$ in eq. 3 is determined for one reported experiment in EWUP Rep. 57 (e.g. Exp. 1). Estimation of crack volume derived from eq. 14 where T is the average infiltration opportunity time yields a value of 0.0674 $m^3.m^{-2}$. The stream size is already calculated and presented in Table 2 and the average infiltration rate is 0.08 $m.d^{-1}$. Substituting with the above values together with a value of T_a = 190 min in eq. 3 yields value of the ratio $\left(\frac{n}{\sqrt{S_o}}\right)^{3/5} = 0.4324$

Comparison between measured and calculated advance time

The advance times for all experiments are calculated with eq. 3 and the results are presented in Table 2. The calculated advance time is plotted against the measured time from Abu-Raya experimental plots in Fig. 3. The results show a good agreement between calculated and measured advance time.

Table 2. Calculate Advance Time to Different Experiments (constant long-term infiltration rate)

Experiment	Stream size x 10^{-4} m^2/s	Estimated crack volume m^3/m^2	Advance time (min)	
			calculated	measured
2	4.80	0.073	224	230
3	4.58	0.070	227	225
4	3.21	0.071	191	198
5	5.18	0.042	71	98
6	15.53	0.041	73	93
7	9.88	0.070	88	99
8	4.09	0.027	92	80
9	10.54	0.060	83	82
10	6.93	0.062	122	125

EXAMPLE 2

A furrow irrigation performed near Greely, Colorado, U.S.A was chosen for the validation of on-farm irrigation efficiency approach. The advance data are given in Table 3. The collected infiltrometer data fit the modified Kostiakov equation of the following form (AL-AZAWI, 1984):

$$y(t) = 0.291\ t^{0.455} + 0.0125\ t \qquad (15)$$

The units of y(t) and t are cm and min, respectively. The flow in the furrow per unit width was 0.003 $m^2.s^{-1}$.

Following the previous procedure, the long-term infiltration rate and the crack volume equal:

$$I_t = 0.132\ T^{-0.545} + 0.0125 \qquad (16)$$

$$V_c = 0.159\ T^{0.455} \qquad (17)$$

The long-term infiltration rate and the crack volume are evaluated at T=172.8 min. This gives:

$I_t = 0.295\ m.d^{-1}$ and

$V_c = 0.0165\ m^3.m^{-2}$

Substituting with those values together with a plot length of 500 m in eq. 3 gives a value of 1.06 for $\left(\frac{n}{\sqrt{S_o}}\right)^{3/5}$

Equation 3 was employed to compute the advance time at various advance distances. The results are tabulated in Table 3. As the calculated advance time is compared with the measured one, it seems that the irrigation efficiency approach overestimated the advance time near the head of the field while reasonable agreement is observed near the tail.

As illustrated by the above two examples, this approach can be applicable in both basin and furrow irrigations.

Table 3. Measured and calculated advance time at various advance distances

Advance distance (m)	100	150	200	250	300	350	400	450	500
Measured advance time (min)	18.4	32.5	47.4	63.6	84.7	107.3	126.8	150.5	172.8
Calculated advance time (min)	25.8	41.5	57.4	72.7	90.7	110.4	129.2	153.7	172.8

ESTIMATION OF DRAINAGE VOLUME

Drainage occurs either when the waterfront does not reach the tail end of the field or when it actually does. The first case has been treated in details in section 5.1 (ICW Note 1697). The second case occurs when the water front reaches at the tail of the field plot (X_e=L) and the operation time of irrigation tool, To, exceeds the time at which waterfront reaches the tail, Te. After Te, a part of the stream size, ($q-I.X_e$), is stored on the field above the amount that was already present on T_e. This storage, Vad, causes a horizontal water table starting in $x = X_e$ (Fig. 4).

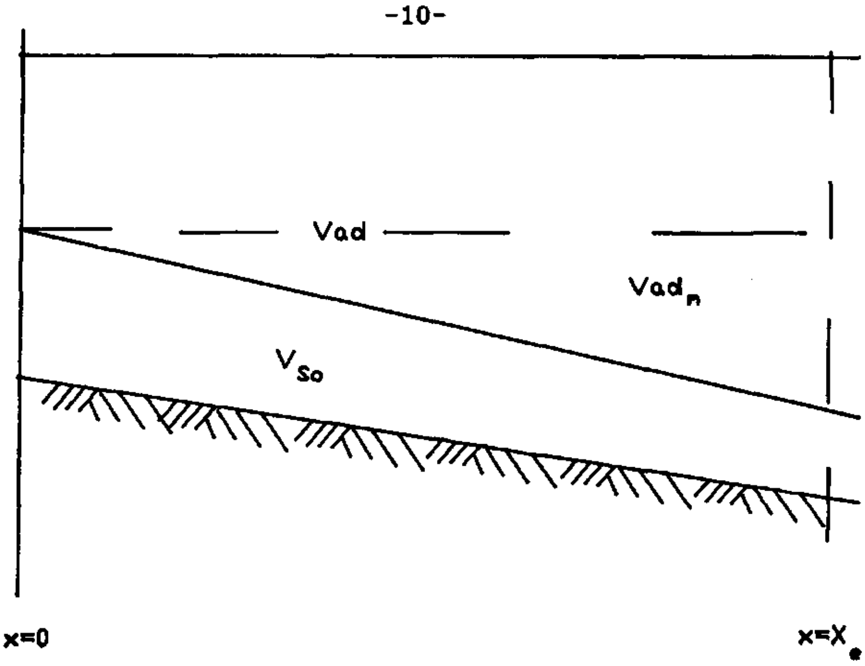


Fig. 4. Definition sketch to eq. 18

The storage volume, V_{ad}, is calculated from:

$$V_{ad} = V_a \cdot L - V_{So} - (T_o - T_e) \cdot L \cdot I - V_c \qquad (18)$$

where:

V_a = actual amount of water delivered to the field

L = plot length

I = infiltration rate

V_{So} = water quantity on the soil surface at time T_o

The storage volume when water level is just horizontally extended up to x=0 (V_{ad_m}) is calculated with:

$$V_{ad_m} = (y_o + 0.5\ X_e \cdot S)\ .\ X_e - V_{So} \qquad (19)$$

$$\text{where: } y_o = \left(\frac{n}{\sqrt{S_o}}\right)^{3/5} \cdot q^{3/5} \qquad (20)$$

Now three main cases can be distinguished:

1. $V_{ad} < 0$
2. $V_{ad} \leqslant V_{ad_m}$ and $V_{ad} > 0$
3. $V_{ad} > V_{ad_m}$ and $V_{ad} > 0$

In case 1, no drainage occurs. The second case has been explained in section 5.2.2 (ICW Note 1697). The third case will be treated herein.

The water depth at x = 0 is:

$$y_o = (V_{ad}+V_{So}) \cdot \frac{1}{X_e} - 0.5\ X_e \cdot S \tag{21}$$

The duration of the infiltration is:

$$T_{i,x} = T_o - T_e + (y_o + x.S) \cdot \frac{1}{I} \tag{22}$$

A number of cases can be distinguished:

Case 1. $T_{i,o} > T_i$ and $T_{i,x_e} > T_i$

The variable T_i is calculated from:

$$T_i = \frac{M_o - M_f - V_c}{I} \tag{23}$$

where:

M_o = total moisture deficit of the soil preceeding irrigation in m

M_f = moisture deficit at field capacity in m

The quantities $T_{i,o}$ and $T_{i,Xe}$ are calculated from eq. 22 for x = 0 and x = X_e, respectively. Then:

$$V_d = V_a - (M_o - M_f) \tag{24}$$

Case 2. $T_{i,o} > T_i$ and $T_{i,X_e} < T_i$

Drainage occurs on $0 < x < X_{max}$. The location of X_{max} is solved from:

$$T_i = \frac{y_o + x \cdot S}{I} - T_{x,s} + T_o \tag{25}$$

The function $T_{x,s}$ is identical to eq. 3. Using a convenient iterative procedure, x_{max} is solved with a starting value of $x_{max} < X_e$. As $x_{min} = 0$, the drainage quantity is calculated from:

$$V_d = \frac{X_{max} - X_{min}}{X_e}\{y_o+T_o \cdot I+0.5(X_{min}+X_{max})\ S\} - \frac{5}{3}\left(\frac{n}{\sqrt{S_o}}\right)^{3/5} \cdot \frac{X_{max} - X_{min}}{X_e} \cdot q_o^{3/5}$$

$$- \frac{5}{8I \cdot X_e} \cdot \frac{5}{3}\left(\frac{n}{\sqrt{S_o}}\right)^{3/5}\{(q_o \cdot I \cdot X_{max})^{8/5} - (q_o - I \cdot X_{min})^{8/5}\}$$

$$- \frac{V_c}{X_e}\{X_{max} \cdot \ln\left(\frac{q_o}{q_o - I \cdot X_{max}}\right) - X_{min} \cdot \ln\left(\frac{q_o}{q_o - I \cdot X_{min}}\right) - \frac{q_o}{I} \cdot \ln\left(\frac{q_o - I \cdot X_{min}}{q_o - I \cdot X_{max}}\right) + (X_{max} - X_{min})\}$$

$$- \frac{X_{max} - X_{min}}{X_e}(M_o - M_f - V_c) \tag{26}$$

Case 3. $T_{i,o} < T_i$ and $T_{i,X_e} > T_i$

Drainage occurs on $X_{min} < x < X_e$. The location x_{min} is solved from eq. 25. As $X_{max} = X_e$, the drainage quantity, V_d, is calculated from eq.26.

Case 4. $T_{i,o} < T_i$ and $T_{i,X_e} < T_i$

In this case, no drainage occurs and

$$V_d = 0 \tag{27}$$

REFERENCES

AL-AZAWI, S.A., 1984. Analysis of the irrigation efficiency parameters. Z.F. Kulturtechnik und Flurbereinigung 25, 11-23.

BOELS, D., 1986. Calculation of on-farm irrigation efficiency. Note 1697, Institute for Land and Water Management Research, Wageningen, Netherlands.

KAFR EL SHEIKH TEAM, 1984. Infiltration studies of Egyptian Vertisols. EWUP Tech. Report No. 57.

RIJTEMA, P.E. and C.W.J. ROEST, 1984. Reuse of Drainage Water IV. Report of a mission to Egypt. Note 1504, Institute for Land and Water Management Research. Wageningen, Netherlands.

SYMBOLS

a, a_1, a_2, b, b_1, b_2	: Constants in the infiltration functions
I	: Infiltration rate in m/s
L	: Plot length in m
M_o	: Total moisture deficit of the soil preceeding irrigation in m
M_f	: Moisture deficit at field capacity in m
n	: Manning's coefficient
Q	: Irrigation water quantity supplied to the field per unit width in m^2
q_o	: Net strbam size per unit length im $m^2.s^{-1}$
q_x	: Unit stream size at any point in $m^2.s^{-1}$
S	: Plot slope
So	: Energy line slope
t	: Time
t_x, t_{x_c}	: Advance time of irrigation streams for non-cracking and cracking soils respectively in sec.
T_e	: Time at which waterfront reaches the tail end in sec
T_o	: Operation time of irrigation tool in sec
V_a	: Actual amount of water delivered to the field in m
V_{ad}	: Amount of water stored on the field above the amount that is already present
V_{ad_m}	: Storage volume when water level is just horizontally extended up to x = 0
V_c	: Crack volume preceeding irrigation in m
V_d	: Drainage volume in m
V_{t_x}	: Amount of water infiltrated into the soil in m
x	: Distance from the head of the field in m
y_o	: Water depth at x=0
y(t)	: Infiltration depth in m