Economical Determination of Storage Phase for Furrow Irrigation System with Free Drainage

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Satisfactory performance of a surface irrigation system depends on the length of the storage phase, which determines the amount of water applied and the cut off time. Longer the duration of the storage phase, bigger is the amount of water delivered to the furrows. These impacts on water loss due to tail water run off and deep percolation cause low efficiency and irrigation costs. Hence, determining the storage phase and cut off time is an economical choice for an irrigation system. This study was done to introduce a methodology for economical determination of the storage phase and the cut off time. A cost function was considered with variables, cost of labour, cost of construction of supply channel and cost of water. For the resulted cost function variable, cut off time was chosen for without irrigation and several levels of deficit in storage time and had undergone present value analysis and cost analysis. These analyses were used in determning the irrigation parameters of application efficiency (E_a), storage efficiency (E_s), percolation loss (P_p) and run off loss (P_e) for the literature data cited by Carvalho and Soares[1] (CS-dataset) and Frizzone[2] (F-dataset). It was observed that the values of all irrigation parameters decreased with the increased level of deficit in cut off time, except for the application efficiency, which increased up to 17% and 24.4% at 31% and 46% level of cut off time deficit for CS and F datasets, respectively.

Keywords **:** Furrow irrigation; Cut off time; Storage phase; Deficit; Cost analysis; Present value analysis

NOTATION

c_c	:	cost of concrete required to construct the supply channel /m^3, \$
c_l	:	wage of a labour/month, \$
c_w	:	cost of water /m^3, \$
C	:	total annual cost of irrigation system/ha, \$
C_c	:	annual cost of supply channel/ha, \$
C_l	:	annual cost of labour/ha, \$
C_o	:	initial cost, \$
C_w	:	annual cost of water /ha, \$
D	:	depreciation/ year, \$
d	:	deficit, %
DT_x	:	duties and taxes over salary, %
E_a	:	application efficiency, %
E_s	:	storage efficiency, %
J	:	interests/year, %
h	:	water height inside the furrow, m
L	:	number of years
K, b	:	advance equation coefficients
n_f	:	number of furrows irrigated/plot
n_l	:	number of labours required/ha
n_m	:	number of months of irrigation/year
n_p	:	number of irrigated plots/ha
P_e	:	run off losses , %
P_p	:	percolation losses, %
Q	:	delivered flow, l/s
T_a	:	advance time, min
T_c	:	cut off time, min
T_{cd}	:	cut off time with deficit, min
T_r	:	reposition time, min
T_x	:	advance time at the end of furrow, min

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PV : present value, \$

w : width of supply channel, m

W : width between furrows, m

y_a : amount applied, mm

y_{def} : average amount applied with deficit, mm

y_{exc} : average amount applied with excess, mm

y_r : amount needed, mm

X : length of furrow, m

X_r : length of furrow where required amount infiltrate, m

β, α : coefficients of accumulated infiltration equation

INTRODUCTION

Water scarcity and low prices for agricultural products have forced irrigators to use water and energy resources efficiently. So, the water supply to the field must be optimum to achieve satisfactory economic yield. Since surface irrigation is the most widely used type of irrigation throughout the world, it is important that these systems must be properly designed and operated to reduce excessive water loss through deep percolation and tail water run off. The low efficiencies in surface irrigation are not inherent to the method but are attributed to poor design, implementation and management[3,4].

The goal of surface irrigation design and management is to maximize system performance. The performance criteria could be economical (*eg*, cost/benefit) or physical (*eg*, application efficiency)[5]. The satisfactory performance of a surface irrigation system depends on the length of the storage phase, which determines the amount of water applied and the cut off time. The duration of the storage phase is the subsequent interval, until the flow is cut off at the field inlet. Longer the duration of storage phase, bigger is the amount of water delivered to the furrows. These impacts on water loss due to tail water run off and deep percolation cause low efficiency and irrigation costs.

The economic criteria of the storage phase can be chosen by transferring different cut off times through a cost function. The different cut off times were obtained for irrigation with and without several levels of deficit in the storage time. The economic study on deficit irrigation in specific circumstances reveals that the technique can increase net farm income[6-9]. The potential benefits of deficit irrigation derive from three factors, increased irrigation efficiency, reduced costs of irrigation and the opportunity cost of water[10]. The comparative study of cut off time against costs with the efficacy allows to obtain the best performance on the project.

The length of the storage phase is an economic decision. Water delivered to the plot should go on until the increased benefits are bigger than the increased costs[2]. Akabassi[11] mentioned that beside the production cost, the irrigation costs may be included in relation to the decision variables, that can not be considered as variables and influencing the final solution.

The main objective of any irrigation project is to deliver the right amount of water at minimal cost. Several factors affect the system and therefore the cost[12]. The costs considered in an irrigation system involve water, supply channel building, operation and maintenance costs. Not much research has been done on economic evaluation of storage phase in furrow irrigation. Hence, an attempt has been made to develop a methodology to determine the economical length of the storage phase in furrow irrigation system with free drainage. The methodology allows to choose the best cut off time according to the best efficiency parameters and lowest losses.

METHODOLOGY

In this study, a cost function was considered to determine the total annual cost of a furrow irrigation system. The cost function includes three variables, the cost of labour, the cost of construction of supply channel and the cost of water. The supply channel is used to deliver water to the furrows. Mathmatically, the different costs are presented below

$$C = C_l + C_c + C_w \quad (1)$$

The annual cost of labour (C_l) is determined from monthly wage of a labour, number of months of irrigation per year and number of labourers needed to operate the irrigation system.

$$C_l = c_l \left(1 + DT_x\right) n_m n_l \quad (2)$$

The annual cost of supply channel (C_c) is determined from the cost of construction of supply channel, number of irrigated plots/ha, number of furrows irrigated/plot and cost of concrete used in construction.

$$C_c = n_p n_f c_c W w b \quad (3)$$

The annual cost of water (C_w) is determined from the number of irrigated plots, number of irrigated furrows per plot and cost of volume of water used.

$$C_w = n_p n_f c_w Q T_c \quad (4)$$

Annual cost of irrigation system can be calculated by substituting C_l , C_e and C_w in the equation(1). The cost was calculated for a seven year period, where in the first year the cost of supply channel building was considered. For the rest of years, it was considered as the maintenance cost at the rate of 0.5% of initial investment, the depreciation of channel capital at an interest of 12% /year, seven years life, and a zero residue value was calculated using equation (5), as given below. This way, the equivalent cost for each year was obtained.

$$D = C_0 \left[\frac{\frac{J}{100}}{\left(1 + \frac{J}{100}\right)^n - 1} \right] \quad (5)$$

The present value (*PV*) was calculated using the yearly cost formula as described in equation (6) which is given below. The lower present values imply lower costs.

$$PV = \sum_{i=0}^{7} \frac{C}{\left(1 + \frac{J}{100}\right)^i} \quad (6)$$

The equations were developed separately for the irrigation with and without deficit, and compared further on. In this study, the infiltrated water profile was considered as linear and the deficit was related to the reposition time. For example, a 5% deficit means a fraction of 95% of the reposition time. The reposition and advance times were determined by using Kostiakov infiltration function as given in equation (7) and power advance function which is given by equation (8), respectively.

$$T_r = \left(\frac{y_r}{\beta}\right)^{\frac{1}{\alpha}} \quad (7)$$

$$T_a = kX^b \quad (8)$$

The equations used to calculate the no deficit irrigation are those presented by Frizzone[2], while with deficit equations are as follows

Cut Off Timing (min)

$$T_{cd} = T_a + T_r \left(\frac{100 - d}{100}\right) \quad (9)$$

Amount Applied (mm)

$$y_a = \frac{QT_{cd}60}{WX} \quad (10)$$

Average Amount Applied in the Area with Excess

The maximum amount applied in this area was considered at the beginning of the furrows (the cut off time with deficit was used in the accumulated infiltration equation) and the minimal amount was the real needed amount.

$$y_{exc} = \frac{\left(\beta T_{cd}^{\alpha}\right) + y_r}{2} \quad (11)$$

Average Amount Applied in the Area with Deficit

The real needed amount was considered to be the maximum infiltrated amount in the area with deficit and, therefore, the reposition time, corrected by the deficit was used to apply at the end of furrows.

$$y_{def} = \frac{y_r + \beta\left[T_a + \left(\frac{100 - d}{100}\right)T_r - T_X\right]^{\alpha}}{2} \quad (12)$$

$$y_{def} = \frac{y_r + \beta\left[\left(\frac{100 - d}{100}\right)T_r\right]^{\alpha}}{2} \quad (13)$$

Furrow Length without Water Deficit

$$T_a = T_{cd} - T_r \quad (14)$$

$$X_r = \left(\frac{T_{cd} - T_r}{k}\right)^{\frac{1}{b}} \quad (15)$$

From equations (9) and (15), the length of furrow where the infiltration of the real needed amount is met, has been derived and presented in equation (16).

$$X_r = \left[\frac{T_a + T_r\left(\frac{100 - d}{100}\right) - T_r}{k}\right]^{\frac{1}{b}} = \left[\frac{T_a + T_r\left(\frac{100 - d}{100} - 1\right)}{k}\right]^{\frac{1}{b}} \quad (16)$$

The effect of the several levels of deficit in cut off time on application efficiency, storage efficiency, percolation loss and run off loss were studied by considering the following formulae.

Application Efficiency (%)

$$E_a = \frac{y_r X_r + y_{def}\left(X - X_r\right)}{y_a X} \times 100 \quad (17)$$

Storage Efficiency (%)

$$E_s = \frac{y_r X_r + y_{def}(X - X_r)}{y_r X} \times 100 \tag{18}$$

Percolation Losses (%)

$$P_p = \frac{(y_{exc} - y_r) X_r}{y_a X} \times 100 \tag{19}$$

Run Off Losses (%)

$$P_e = \frac{y_a X - X_r y_{exc} - y_{def}(X - X_r)}{y_a X} \times 100 \tag{20}$$

RESULTS AND DISCUSSION

The proposed methodology was applied for two input data sets adopted from Carvalho and Soares[1](CS-dataset) and Frizzone[2] (F-dataset), as presented in Table 1. The results obtained by the proposed methodology are presented in Table 2 and Table 3 for CS and F-datasets, respectively. From Table 2 and Table 3, it is observed that all the studied parameters have shown a decreasing trend, except the parameter application efficiency, which increased with decrease of cut off time. Therefore, it implies reduction of volume of water applied and the costs. Considering the acceptable values for $E_a \geq 60\%$, $E_s \geq 90\%$, $P_p \leq 15\%$ and $P_e \leq 8\%$, all the results stayed inside those limits, except for P_e which was high for all the evaluated cases. So, for CS and F-datasets, the higher permissible deficit was chosen, considering a value of X_r bigger than 50% of furrow length, since this presented lower values of PV, E_s, P_p and P_e and higher of E_a.

Table 1 Input data for evaluating the proposed methodology

Input data	CS-dataset*	F-dataset**
Concrete channel cost, \$/m^3	90.00	90.00
Water cost, \$/m^3	0.05	0.05
Workers earnings, \$/month	120.00	120.00
DT_x , taxes factor over salary	1	1
Months of operation, month/year	7	7
Number of workers /ha	1.5	1.5
Number of plots/ha	2	2
Number of furrows/plot	137	137
Width between furrows	1	1
Channel width, m	1.5	1.5
Water height in furrow, m	0.15	0.15
Required amount, mm	40	35
Inflow (l/s) to the furrow	0.78	1.00
Furrow length, m	100	200
K	0.0898	0.0866
B	1.351	1.316
β	0.79	1.8
α	0.88	0.62

Source : * : Carvalho and Soares[1], and **Frizzone[2]

Table 2 Effect of the level of cut off time deficit on the irrigation parameters for CS-dataset

Deficit, %	T_c, min	X_r, m	PV, \$	E_a, %	E_s, %	P_p, %	P_e, %
0	131.68	100.00	59059.34	64.91	100.00	14.54	20.56
1	130.82	98.58	58874.26	65.33	99.99	14.16	20.51
3	129.09	95.72	58504.12	66.17	99.94	13.40	20.43
5	127.36	92.83	58133.98	67.00	99.84	12.65	20.35
7	125.63	89.91	57763.83	67.82	99.69	11.90	20.28
9	123.90	86.95	57393.69	68.62	99.48	11.17	20.21
11	122.17	83.96	57023.54	69.41	99.22	10.44	20.15
13	120.44	80.93	56653.40	70.18	98.90	9.72	20.09
15	118.71	77.86	56283.25	70.94	98.52	9.02	20.05
17	116.98	74.75	55913.11	71.67	98.09	8.32	20.01
31	104.88	51.42	53322.10	75.98	93.23	3.88	20.00

Table 3 Effect of the level of cut off time deficit on the irrigation parameters for F-dataset

Deficit, %	T_c, min	X_r, m	PV, \$	E_a, %	E_s, %	P_p, %	P_e, %
0	212.27	200.00	89121.94	54.96	100.00	11.68	33.35
1	211.07	198.03	88793.02	55.27	100.00	11.50	33.23
3	208.67	194.06	88135.18	55.89	99.97	11.13	32.98
5	206.27	190.06	87477.33	56.51	99.92	10.75	32.73
7	203.88	186.04	86819.49	57.14	99.85	10.38	32.48
9	201.48	181.99	86161.64	57.76	99.74	10.01	32.24
11	199.08	177.92	85503.80	58.38	99.62	9.63	31.99
13	196.69	173.81	84845.95	59.00	99.46	9.26	31.74
15	194.29	169.67	84188.11	59.61	99.27	8.89	31.50
17	191.89	165.50	83530.26	60.23	99.06	8.52	31.25
46	157.13	100.30	73991.51	68.37	92.09	3.40	28.22

Further, the behaviour of the studied parameters with respect to the level of deficit in cut off time can be explained further by analyzing the percentage relative change of the parameters. The relative percentage change of a parameter represents the absolute change with respect to the initial value. The relative percentage change of the studied parameters for CS and F-datasets are shown in Figure 1 and Figure 2, respectively. It is observed from the figures that all the parameters are declining, except the application efficiency (E_a). The large negative changes in the parameters, P_p and X_r show that the parameters are declining rapidly or strongly with respect to the level of deficit. In case of P_p, the relative percentage change declined up to 73.32% and 70.89% at 31% and 46% level of deficit for CS and F-datasets, respectively. Whereas in case of X_r, the declination is up to 48.58% and 49.85% at 31% and 46% level of deficit. The small

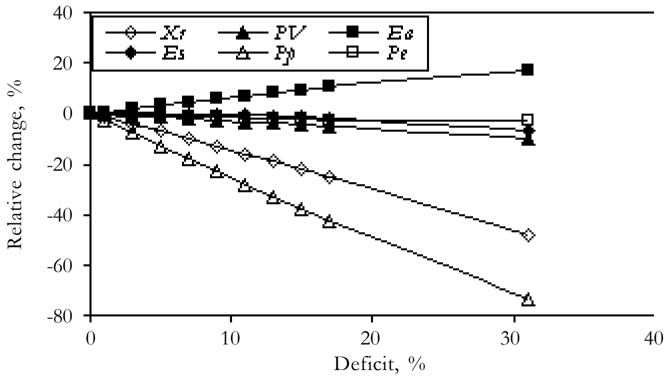

Figure 1 Relative percentage change of irrigation parameters with change in level of deficit for CS-dataset

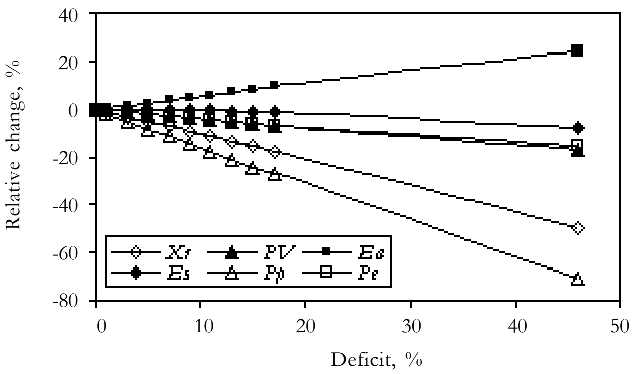

Figure 2 Relative percentage change of irrigation parameters with change in level of deficit for F-dataset

negative changes in the parameters P_e, E_s and PV show that the parameters are declining steadily or weekly with the level of deficit. In the case of CS dataset, the relative percentage change for P_e, E_s and PV at 31% level of deficit was 2.71%, 6.77% and 9.71%, respectively. Whereas in case of F-dataset, the relative percentage change for P_e, E_s and PV at 46% level of deficit was 15.38%, 7.91% and 16.97%, respectively. The parameter, application efficiency (E_a) is growing up to 17% and 24.4% at 31% and 46% level of deficit for CS and F-datasets, respectively.

CONCLUSIONS

For furrow irrigation with free drainage, a methodology has been proposed to determine the economical duration of the reposition phase, through the calculation of present value of project costs for a seven year period. The methodology allows to choose the best cut off time according to the best efficiency parameters and lowest losses. The methodology was validated for CS and F-datasets. In both the cases, a decreased trend was observed for all the parameters (X_r, PV, E_s, P_p and P_e) with decrease of cut off time, except for (E_a). The higher permissible deficit was chosen by considering a value of X_r, bigger than 50% of furrow length to yield lower acceptable values of PV, E_s, P_p and P_e and higher value of E_a. The percentage relative error for P_p and X_r was found declining rapidly and for P_e, E_s and PV, it was declining steadily. Whereas in case of E_a, the relative error was growing to 17% and 24.4% at 31% and 46% level of deficit in storage phase.

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