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Guidelines to Optimal Design of Furrow Irrigation Based on Plants, Soil and Furrow Specifications

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Abstract: *In order to optimize the usage of water in agriculture, it is necessary to increase the efficiency of irrigation systems, especially those of surface irrigation. One of the steps to be made to achieve this goal is the optimal design of surface irrigation. It this article the design variables of furrow irrigation, that includes length of furrow, inflow rate and irrigation time (time of cut-off), were calculated to minimize the irrigation costs, the objective function, and to obtain a maximum application efficiency. The objective function encompasses water, labor, head ditch and furrow digging (ditch constructions) costs. Labor cost is irrigation time's function and the latter is dependent on water advance period in the furrows. Therefore, it is necessary for the objective function to apply explicit and accurate equation in order to calculate time of advance. Because in none of the accurate methods for furrow irrigation design, such as zero-inertia modeling, the advance time is explicitly calculated, therefore in this research the equation obtained by Valiantzas, which he extracted from the results of zero-inertia modeling, was used. In the objective function in addition to the design variables the specifications of soil, furrow and net irrigation requirement also exist. Therefore, it is possible to calculate design variables and afterwards the irrigation efficiency for different soil types and plant types. In this article this task was performed with different soil types and in accordance with different requirements for irrigation and the results are presented in the tables.*

Keywords: *Furrow Irrigation, Advance Time, Optimization*

1. INTRODUCTION

One of the most effective steps towards increasing the efficiency of the surface irrigation is design optimization. Generally, we can divide the methods of surface irrigation design or methods for time of advance calculation (an important parameter in design) into three groups presented below:

1. Simple methods such as SCS. Valiantzas (2001) have shown that by using this method significant errors in calculating the time of advance were detected. Reddy and Clyma (1981) and Reddy and Apolayo (1991) have used SCS equation for a furrow optimal design and they have considered total cost of irrigation as their objective.
2. Ordinary methods such as kinematic wave model, zero-inertia model and dynamic wave model. First of all, these methods are complicated, and secondarily, it is not possible by using them to calculate explicit time of advance. Strelkoff and Katapodes (1977) and Elliott and others (1982) held the method of zero-inertia modeling to be suitable to calculate the time of advance [1-16].
3. Volume balance models. First of all, in these models it is assumed that the coefficients of the surface flow and subsurface flow during the whole period of advance time stay constant, and secondarily, these methods are dependent on normal depth. Walker and Skogerboe (1987) used the volume balance models to calculate time of advance.

In order to optimize furrow irrigation none of the aforementioned methods were suitable, because by using those it is not possible to calculate the explicit and accurate time of advance. Optimal design requires a mathematical equation to explicitly calculate the time of advance necessary for the objective function. In the research presented in the present article total cost necessary for one irrigation session including labor, water and ditch construction is considered to be the functional objective that needs to be minimized. It is clear that labor cost is a function of irrigation time and the latter is a function of advance time. Considering the weak points of the aforementioned methods, in this research the equation introduced by Valiantzas (2001) was used to calculate the time of advance. This is an explicit equation for advance time calculation that Valiantzas obtained it from the results of zero-inertia modeling and it is having a high accuracy [17-37].

2. MATERIAL AND METHODS

In order to irrigate a given piece of a farmland by the method of furrow irrigation it is necessary to divide it into several irrigationsection. Each of the irrigation sections contains a certain number of furrows that are being irrigated simultaneously. Valiantzas (2001) presented an equation to calculate total cost of one irrigation session of a farmland that this equation has been changed by Shayannejad (2004) in the following way:

$$C_t = \frac{W_f . L_f . Q_0 . T_{co}}{W . L}\left(C_w + \frac{C_l}{Q_t}\right) + \frac{W_f . L_f}{N_i}\left(\frac{C_f}{W} + \frac{C_d}{L}\right) \tag{1}$$

Where regarding the above:

L_f = length of a farmland in meters (along the furrows)

W_f = width of a farmland in meters (in the vertical direction along the furrows)

Q_0 = inflow rate to eachfurrow (m^3/min)

Q_t = total available flow rate (m^3/min)

L = length of each furrow (m)

W = width of each furrow (m)

C_w = cost of water volume unit in Iranian rials per cubic meter

T_{co} = cut-off time or time of irrigation (min)

C_l = labor cost for unit of time in Iranian rials per minute

C_f = furrowdigging cost in length unit of a furrow in Iranian rials per meter

N_i = number of irrigation eventsduring the growing season

C_d = head ditch diggingcost in length unit of a ditch in Iranian rials per meter

C_t = total cost of a onetime irrigation session of a farmland in Iranian rials

Equation (1) indicates that total cost of the objective function is formed by the the three Q_0, T_{co}, L variables, and can be written as a function of the two other variables. In order to do that, at first this addition is being written:

$$T_{co} = T_l + T_r \tag{2}$$

Where regarding the above:

T_l = water advance time to the end of a furrow (min)

T_r = time of intake opportunity according to net irrigation requirement (min)

In order to calculate T_r we can use any of the infiltration equations. If Kostiakov's equation is to be used, the calculation is as follows:

$$Z = K.T^{\alpha} \tag{3}$$

$$T_r = \left(\frac{Z_r}{K}\right)^{1/\alpha} \tag{4}$$

Where regarding the above:

Z = depth of the percolated (infiltrated) water (m)

T = percolation (infiltration) time (min)

Z_r = net irrigation requirement (m)

K, α = infiltration coefficients of Kostiakov's equation

To calculate T_l the equation presented by Valiatzas (2001) is used:

$$T_l = (1 + 0.15\alpha).L.A_0 / Q_0 + (\sigma_z.K.L/Q_0)^{1/(1-\alpha)} \tag{5}$$

Where regarding the above:

A_0 = area of cross section at the end of upstream of the furrow (m^2)

σ_z = subsurface flow shape factor. This coefficient is calculated by the following equation:

$$\sigma_z = \frac{\alpha\pi.(1-\alpha)}{Sin(\alpha\pi)} \tag{6}$$

A_0 value is calculated by using Manning's equation where the furrow form coefficients are calculated it the following way:

$$A_0 = \left(\frac{n^2 Q_0^{\ 2}}{3600 S_0.\rho_1}\right)^{1/\rho_2} \tag{7}$$

Where regarding the above:

n = Manning's roughness coefficient

S_0 = furrow bed slope (m/m, in decimal form)

ρ_1, ρ_2 = furrow shape coefficients. These coefficients in accordance with Manning's equation are calculated as follows:

$$A.R^{4/3} = \rho_1 A^{\rho_2} \tag{8}$$

Where regarding the above:

A = flow cross section (m^2)

R = Hydraulic radius (m)

Finally, by substituting the (2), (4), and (5) equations in the equation (1), the equation is obtained indicating that C_t is a function of the two Q_0 and L variables. This equation can be written as follows:

$$C_t = f(Q_0, L) \tag{9}$$

if L is assumed to be constant and derivative equation (9) in respect to Q_0 was made equal to zero, the value of inflow rate that leads to minimum cost is obtained by the following:

$$C_1.Q_0^{2/\rho_2 - 1} - C_2.Q_0^{1/(\alpha-1)} + T_r = 0 \tag{10}$$

$$C_1 = \left(\frac{n^2}{\rho_1 S_0}\right)^{1/\rho_2} \left(\frac{2L}{\rho_2}\right)(1 + 0.15\alpha) \tag{11}$$

$$C_2 = \frac{\alpha}{(1-\alpha)(\sigma_z KL)^{1/(1-\alpha)}} \tag{12}$$

Afterwards by using equation (2) it is possible to calculate irrigation time and by using

$$E_a = \frac{Z_r.W.L}{Q_0.T_{co}} \times 100 \tag{13}$$

Formula to calculate irrigation efficiency,

Where regarding the above E_a is irrigation efficiency percentage. According to the equation (1) along with the minimization of C_t results of Q_c, T_{co} are also minimized. Therefore, in respect to the equation (13) the irrigation efficiency is maximized [38-98].

To summarize it is possible to say, that the method described in this research is based on principal of cost minimization and irrigation efficiency maximization and is a result of the calculations related to inflow rate to furrow, length of furrow, irrigation time and irrigation efficiency. In order to check length of furrow variables, the above method was solved by using furrows of different length, and for each of the lengths an inflow rate in accordance with a particular length is obtained [99-204].

3. Conclusion and Result

As for example, the equation's solution and results (10) for the furrow having the following specifications (an ordinary furrow), with taking into account various values of furrow length, irrigation requirements and soil patterns (with Intake Family or IF standard) and being in accordance with the Newton-Raphson method are provided in the tables below.

$n = 0.01$, $S_0 = 0.001$, $\rho_1 = 0.6$, $\rho_2 = 2.8$

The data presented in the ordinary tables of furrow irrigation design (provided by Boucher) differ from the data provided in the following tables. In addition to this in the last table information related to the form of a furrow is included. It is necessary to mention that numbers in the following tables are numbers of inflow rates to a furrow. These numbers should not exceed erosion inflow rates to a furrow.

Table (1): Guide to the design of furrow irrigation

IF=0.1	Qo(lit/s)				IF=0.3	Qo(lit/s)			
L(m)	Zr =.05m	Zr =.075m	Zr =.1m	Zr =.125m	L(m)	Zr =.05m	Zr =.075m	Zr =.1m	Zr =.125m
20	0.02	0.01	0.01	0.01	20	0.07	0.06	0.05	0.04
30	0.03	0.02	0.01	0.01	30	0.1	0.08	0.07	0.06
40	0.03	0.02	0.02	0.02	40	0.14	0.11	0.09	0.08
50	0.04	0.03	0.02	0.02	50	0.18	0.13	0.11	0.1
60	0.05	0.04	0.03	0.02	60	0.23	0.17	0.14	0.12
70	0.06	0.04	0.03	0.03	70	0.26	0.2	0.16	0.14
80	0.06	0.05	0.04	0.03	80	0.3	0.23	0.2	0.16
90	0.07	0.05	0.04	0.03	90	0.33	0.25	0.22	0.2
100	0.08	0.06	0.05	0.04	100	0.36	0.3	0.24	0.22
110	0.1	0.06	0.05	0.04	110	0.4	0.33	0.27	0.24
120	0.11	0.07	0.05	0.04	120	0.45	0.35	0.29	0.26
130	0.11	0.07	0.06	0.05	130	0.49	0.38	0.31	0.28
140	0.12	0.08	0.06	0.05	140	0.52	0.41	0.35	0.3
150	0.13	0.08	0.07	0.05	150	0.56	0.44	0.37	0.32
160	0.14	0.09	0.07	0.06	160	0.59	0.47	0.4	0.34
170	0.14	0.09	0.07	0.06	170	0.63	0.49	0.42	0.36
180	0.17	0.1	0.08	0.06	180	0.66	0.52	0.45	0.38
190	0.18	0.12	0.08	0.07	190	0.69	0.55	0.47	0.42
200	0.19	0.12	0.09	0.07	200	0.73	0.59	0.5	0.44
210	0.2	0.13	0.09	0.07	210	0.76	0.62	0.52	0.46
220	0.2	0.13	0.09	0.08	220	0.81	0.65	0.54	0.48
230	0.21	0.14	0.1	0.08	230	0.85	0.68	0.57	0.5
240	0.22	0.15	0.1	0.08	240	0.88	0.7	0.59	0.52
250	0.23	0.15	0.1	0.09	250	0.92	0.73	0.61	0.54
260	0.24	0.16	0.11	0.09	260	0.95	0.76	0.64	0.57
270	0.25	0.16	0.11	0.09	270	0.99	0.79	0.66	0.59
280	0.26	0.17	0.12	0.1	280	1.02	0.82	0.68	0.61
290	0.26	0.17	0.14	0.1	290	1.06	0.85	0.71	0.63
300	0.27	0.18	0.14	0.1	300	1.09	0.87	0.73	0.65
310	0.28	0.18	0.15	0.11	310	1.12	0.9	0.77	0.67
320	0.29	0.19	0.15	0.11	320	1.16	0.93	0.79	0.69
330	0.31	0.19	0.15	0.11	330	1.19	0.96	0.82	0.71
340	0.32	0.22	0.16	0.12	340	1.23	0.98	0.84	0.73
350	0.33	0.22	0.16	0.12	350	1.26	1.01	0.87	0.75
360	0.34	0.23	0.17	0.12	360	1.29	1.04	0.89	0.77
370	0.35	0.24	0.17	0.13	370	1.33	1.07	0.91	0.79
380	0.36	0.24	0.18	0.13	380	1.36	1.09	0.94	0.82
390	0.37	0.25	0.18	0.15	390	1.39	1.12	0.96	0.84
400	0.37	0.25	0.18	0.15	400	1.42	1.15	0.99	0.86

Continued Table (1): Guide to the design of furrow irrigation

IF=0.5	Qo(lit/s)				IF=0.8	Qo(lit/s)			
L(m)	Zr =.05m	Zr =.075m	Zr =.1m	Zr =.125m	L(m)	Zr =.05m	Zr =.075m	Zr =.1m	Zr =.125m
20	0.12	0.1	0.09	0.09	20	0.22	0.19	0.17	0.15
30	0.19	0.15	0.14	0.13	30	0.34	0.29	0.26	0.23
40	0.27	0.22	0.18	0.17	40	0.45	0.39	0.35	0.32
50	0.34	0.27	0.24	0.22	50	0.57	0.49	0.43	0.4
60	0.4	0.34	0.29	0.26	60	0.68	0.58	0.53	0.48
70	0.48	0.39	0.33	0.31	70	0.79	0.68	0.62	0.57
80	0.54	0.45	0.38	0.35	80	0.89	0.79	0.7	0.65
90	0.61	0.5	0.44	0.39	90	1.02	0.88	0.79	0.73
100	0.67	0.55	0.49	0.43	100	1.13	0.98	0.87	0.81
110	0.73	0.61	0.54	0.49	110	1.23	1.07	0.97	0.89
120	0.79	0.67	0.59	0.53	120	1.34	1.17	1.06	0.97
130	0.86	0.73	0.63	0.58	130	1.45	1.26	1.14	1.04
140	0.94	0.78	0.68	0.62	140	1.55	1.35	1.23	1.12
150	1	0.84	0.73	0.66	150	1.66	1.44	1.32	1.22
160	1.06	0.89	0.77	0.71	160	1.78	1.55	1.4	1.3
170	1.13	0.95	0.82	0.75	170	1.88	1.65	1.49	1.38
180	1.19	1	0.88	0.79	180	1.99	1.74	1.57	1.46
190	1.25	1.05	0.93	0.83	190	2.09	1.83	1.66	1.53
200	1.31	1.11	0.98	0.88	200	2.2	1.93	1.74	1.61
210	1.38	1.16	1.03	0.92	210	2.3	2.02	1.82	1.69
220	1.44	1.21	1.07	0.96	220	2.4	2.11	1.91	1.77
230	1.5	1.26	1.12	1	230	2.51	2.21	2.01	1.85
240	1.56	1.31	1.17	1.06	240	2.61	2.3	2.09	1.93
250	1.64	1.38	1.22	1.1	250	2.71	2.39	2.18	2.01
260	1.7	1.44	1.26	1.15	260	2.81	2.48	2.26	2.08
270	1.76	1.49	1.31	1.19	270	2.91	2.57	2.34	2.16
280	1.82	1.54	1.36	1.23	280	3.03	2.66	2.43	2.24
290	1.88	1.6	1.4	1.28	290	3.13	2.77	2.51	2.32
300	1.94	1.65	1.45	1.32	300	3.23	2.86	2.6	2.39
310	2.01	1.7	1.5	1.36	310	3.33	2.95	2.68	2.47
320	2.07	1.76	1.54	1.41	320	3.43	3.04	2.76	2.56
330	2.13	1.81	1.59	1.45	330	3.54	3.13	2.85	2.64
340	2.19	1.86	1.64	1.49	340	3.64	3.22	2.93	2.72
350	2.25	1.91	1.68	1.53	350	3.74	3.31	3.01	2.8
360	2.31	1.96	1.73	1.58	360	3.83	3.4	3.1	2.88
370	2.37	2.02	1.77	1.62	370	3.93	3.49	3.18	2.95
380	2.43	2.07	1.84	1.66	380	4.03	3.58	3.26	3.03
390	2.49	2.12	1.88	1.7	390	4.13	3.67	3.34	3.11
400	2.54	2.17	1.93	1.75	400	4.23	3.76	3.42	3.19

Continued Table (1): Guide to the design of furrow irrigation

IF=1	Qo(lit/s)				IF=1.5	Qo(lit/s)			
L(m)	Zr =.05m	Zr =.075m	Zr =.1m	Zr =.125m	L(m)	Zr =.05m	Zr =.075m	Zr =.1m	Zr =.125m
20	0.29	0.25	0.21	0.2	20	0.42	0.37	0.34	0.32
30	0.43	0.37	0.34	0.32	30	0.64	0.56	0.52	0.48
40	0.58	0.51	0.45	0.42	40	0.84	0.74	0.69	0.65
50	0.72	0.63	0.58	0.52	50	1.04	0.94	0.86	0.81
60	0.86	0.75	0.69	0.65	60	1.26	1.13	1.03	0.97
70	1.01	0.89	0.8	0.75	70	1.46	1.31	1.21	1.13
80	1.15	1.01	0.91	0.86	80	1.66	1.49	1.38	1.28
90	1.29	1.14	1.04	0.96	90	1.87	1.68	1.55	1.46
100	1.43	1.26	1.15	1.06	100	2.07	1.86	1.72	1.62
110	1.56	1.38	1.27	1.17	110	2.27	2.04	1.88	1.78
120	1.69	1.5	1.38	1.28	120	2.46	2.22	2.05	1.94
130	1.84	1.64	1.49	1.39	130	2.66	2.4	2.23	2.09
140	1.98	1.76	1.6	1.5	140	2.85	2.58	2.4	2.25
150	2.12	1.88	1.71	1.6	150	3.04	2.75	2.56	2.41
160	2.25	2	1.82	1.7	160	3.25	2.94	2.73	2.56
170	2.38	2.12	1.93	1.81	170	3.44	3.12	2.9	2.71
180	2.52	2.24	2.04	1.91	180	3.63	3.3	3.06	2.89
190	2.65	2.36	2.17	2.02	190	3.82	3.48	3.23	3.04
200	2.78	2.48	2.28	2.12	200	4.01	3.65	3.39	3.2
210	2.91	2.6	2.39	2.22	210	4.2	3.83	3.55	3.36
220	3.05	2.71	2.5	2.32	220	4.39	4	3.72	3.51
230	3.18	2.85	2.61	2.43	230	4.57	4.18	3.88	3.67
240	3.32	2.97	2.72	2.53	240	4.76	4.35	4.06	3.82
250	3.45	3.09	2.83	2.65	250	4.96	4.52	4.22	3.98
260	3.58	3.2	2.94	2.75	260	5.14	4.69	4.38	4.13
270	3.7	3.32	3.05	2.85	270	5.33	4.86	4.55	4.29
280	3.83	3.44	3.16	2.96	280	5.52	5.05	4.71	4.44
290	3.96	3.56	3.27	3.06	290	5.7	5.22	4.87	4.6
300	4.09	3.68	3.38	3.16	300	5.88	5.39	5.03	4.75
310	4.22	3.79	3.49	3.27	310	6.07	5.57	5.2	4.9
320	4.34	3.91	3.59	3.37	320	6.25	5.74	5.36	5.05
330	4.47	4.03	3.7	3.47	330	6.43	5.91	5.52	5.2
340	4.59	4.14	3.81	3.57	340	6.61	6.08	5.68	5.37
350	4.72	4.26	3.93	3.67	350	6.79	6.25	5.84	5.53
360	4.86	4.37	4.04	3.78	360	6.97	6.42	6	5.68
370	4.98	4.49	4.15	3.88	370	7.14	6.59	6.16	5.83
380	5.11	4.6	4.26	3.98	380	7.32	6.75	6.32	5.99
390	5.23	4.71	4.36	4.08	390	7.52	6.92	6.47	6.14
400	5.36	4.84	4.47	4.18	400	7.7	7.09	6.63	6.29

Continued Table (1): Guide to the design of furrow irrigation

IF=2	Qo(lit/s)				IF=3	Qo(lit/s)			
L(m)	Zr =.05m	Zr =.075m	Zr =.1m	Zr =.125m	L(m)	Zr =.05m	Zr =.075m	Zr =.1m	Zr =.125m
20	0.54	0.5	0.45	0.43	20	0.8	0.72	0.68	0.63
30	0.83	0.74	0.69	0.65	30	1.2	1.09	1.01	0.96
40	1.1	1	0.92	0.87	40	1.58	1.44	1.35	1.27
50	1.37	1.24	1.15	1.08	50	1.97	1.8	1.69	1.6
60	1.63	1.48	1.38	1.29	60	2.35	2.16	2.01	1.92
70	1.9	1.73	1.61	1.52	70	2.72	2.5	2.35	2.23
80	2.16	1.97	1.83	1.73	80	3.09	2.85	2.68	2.54
90	2.42	2.21	2.05	1.94	90	3.47	3.2	3.01	2.85
100	2.68	2.44	2.28	2.16	100	3.84	3.55	3.34	3.18
110	2.93	2.68	2.51	2.37	110	4.21	3.89	3.66	3.49
120	3.2	2.91	2.73	2.57	120	4.57	4.23	3.98	3.8
130	3.45	3.16	2.95	2.78	130	4.94	4.57	4.31	4.11
140	3.71	3.4	3.17	3.01	140	5.3	4.9	4.64	4.41
150	3.96	3.63	3.39	3.22	150	5.66	5.25	4.96	4.72
160	4.21	3.86	3.61	3.43	160	6.01	5.59	5.28	5.03
170	4.45	4.1	3.83	3.64	170	6.36	5.93	5.6	5.33
180	4.7	4.33	4.04	3.85	180	6.71	6.26	5.91	5.65
190	4.96	4.56	4.28	4.05	190	7.06	6.59	6.23	5.95
200	5.2	4.78	4.5	4.26	200	7.42	6.92	6.54	6.26
210	5.45	5.02	4.71	4.47	210	7.77	7.25	6.86	6.56
220	5.69	5.25	4.93	4.67	220	8.11	7.58	7.18	6.87
230	5.94	5.48	5.15	4.88	230	8.46	7.9	7.5	7.17
240	6.18	5.71	5.36	5.08	240	8.8	8.24	7.81	7.47
250	6.42	5.94	5.58	5.29	250	9.14	8.57	8.13	7.77
260	6.66	6.16	5.79	5.51	260	9.48	8.89	8.44	8.07
270	6.89	6.39	6.01	5.71	270	9.82	9.22	8.75	8.37
280	7.13	6.62	6.22	5.92	280	10.15	9.54	9.06	8.67
290	7.38	6.84	6.43	6.13	290	10.5	9.86	9.37	8.96
300	7.62	7.06	6.64	6.33	300	10.84	10.18	9.68	9.26
310	7.86	7.29	6.86	6.53	310	11.17	10.5	9.99	9.57
320	8.09	7.51	7.08	6.74	320	11.51	10.82	10.29	9.87
330	8.33	7.73	7.3	6.94	330	11.84	11.14	10.6	10.17
340	8.56	7.96	7.51	7.15	340	12.17	11.46	10.9	10.46
350	8.79	8.18	7.72	7.35	350	12.5	11.77	11.2	10.76
360	9.03	8.41	7.93	7.55	360	12.83	12.1	11.52	11.05
370	9.26	8.63	8.14	7.75	370	13.16	12.42	11.83	11.35
380	9.49	8.85	8.35	7.95	380	13.48	12.73	12.13	11.64
390	9.72	9.07	8.56	8.16	390	13.81	13.05	12.44	11.94
400	9.95	9.29	8.77	8.36	400	14.13	13.36	12.74	12.23

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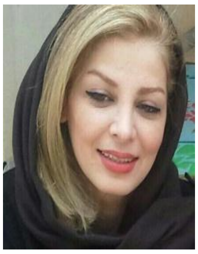

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