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# Developing an Optimal Design Model of Furrow Irrigation Based on the Minimum Cost and Maximum Irrigation Efficiency

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**Abstract**

The main objective of the furrow irrigation is appropriate selection of planning and managerial variables. These variables are: the furrow length, flow rate to the furrow and cut-off time. These variables are computed through optimization based on minimizing the total irrigation cost and maximizing the application efficiency of irrigation. The objective function has been formed based on costs of the water, worker and head ditch and furrow digging. Therefore, in the objective function, an equation should be considered for computing the water advance period in a clear and precise manner. Since none of the exact methods used for planning furrow irrigation like zero inertia, compute the advance time explicitly, thus in this research the Valiatzas equation has been used which has been deduced from the results of the zero inertia model. In the objective function, in addition to the planning variables, soil characteristics, furrow and net irrigation requirement have been included. Therefore, the design variables and irrigation efficiency can be computed for each type of soil and specific plant. A sample of this design has been presented in this paper.

**Keywords:** Furrow, Advance Time, Optimization

## 1. Introduction

Regarding the arid conditions in Iran and un-usability of pressurized irrigation in all conditions, an increase in the efficiency of surface irrigation is essential. Optimal planning of surface irrigation methods is one of the effective steps to achieve this purpose. Generally, the surface irrigation planning methods or methods for computing the advance time (an important parameter in planning) can be categorized into the following groups:

Group one: simple methods like the SCS method. Reddy and and Clyma (1981) and Reddy and Apolayo (1991) used the SCS equation for optimal planning of furrows and considered the total irrigation expense as the objective function. However, findings showed that this method led to considerable errors in computing the advanced time (Valiantzas, 2001a; Banti et al., 2011).

Group two: numerical methods include the kinematic wave, zero inertia and dynamic wave models. These methods are complex and also cannot compute the advance time explicitly (Strelkoff and Katopodes, 1977). Strelkoff and Katopodes (1977) and Elliott et al. (1982) used the zero inertia models for computing the advance time. The optimum conditions and alternate-furrow fertigation strongly reduce water and nitrate losses compared with conventional furrow irrigation. The simulation-optimization model is a valuable tool for alleviation of the environmental impact of furrow irrigation (Ebrahimian et al., 2013a, b; Pais et al., 2010).

Ostad-Ali-Askari and Shayannejad (2015a, b), reported that input variables of a mathematical model were effective parameters on deep percolation such as bed slope, inflow rate and coefficients of soil infiltration. These variables were measured in 16 farms of Zayanderood basin. Comparison of estimated and measured deep percolation showed that the error of model was 1.73%.

Gonc et al. (2011) reported that adopting water and deficit irrigation were generally difficult in economic terms, thus it is necessary to support the farmers.

The water flow of surface irrigation exhibits a major characteristic which is the existence of wet-dry boundary (Albert et al., 2011; Hosseini et al., 2014). In numerical simulation, due to the anti-diffusion characteristic of the roughness term of the Saint-Venant equations, wet-dry boundary of the surface flow can impact the stability of momentum conservation equation and reduce the simulation accuracy of iterative coupled models (Dong et al., 2013; Fenoglio et al., 2007).

Group three: the volume balance model. In this model the surface and subsurface shape factors during the advance stage are assumed to be constant. Also, this model is based on the normal depth. Walker and Skogerboe (1987) reported that the volume balance model is more appropriate for advance computation. Users of volume balance model need to be aware that uncertain surface volume calculations can lead to potentially large volume balance errors. Thus, these results need to be interpreted carefully (Bautista et al., 2012).

None of the above mentioned methods seems appropriate in planning the optimal furrow irrigation, since these methods cannot compute the advance time explicitly and precisely (Raeisi-Vanani et al., 2015). Optimal planning needs a mathematical equation for explicit computation of the advance time and using in the objective function (Soltani-Todeshki et al., 2015). In this paper the total required cost for once irrigation including the workforce cost, water, furrows and ditch digging has been considered as the objective function which should be minimized. Obviously, the workforce cost is a function of the irrigation time which depends on the advance time. In this research the equation was suggested by Valiantzas (2001b) used for the computation of the advance time. This is an explicit equation for the computation of the advance time. Valiatzas equation obtained based on the results of the zero inertia model with high precision.

**2. Methodology**

Model development for irrigation a piece of specified farm land through the furrow, it must be divided into a number of irrigation sets ( $N_s$ ). Each irrigation section composes a number of furrows which are concurrently irrigated. The arrangement of irrigation sets for better understand of signs and the method of this paper are presented in fig. 1.

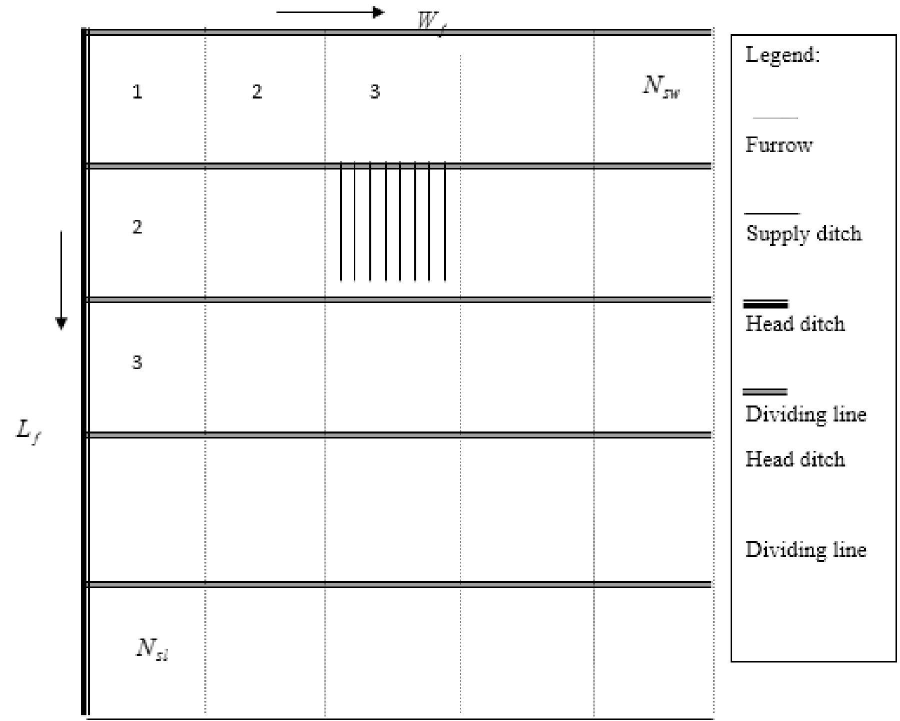


Fig. 1. Furrow irrigation arrangement.

Where, $N_{sl}$ is total number of irrigation sets in the direction of furrows; $N_{sw}$ is total number of irrigation sets in the direction of perpendicular to furrows; $L_f$ is length of the farm in meters (in the direction of furrows); $W_f$ is width of the farm in meters (in the direction of perpendicular to furrows); $Q_0$ is inflow flow rate to each furrow (m$^3$/min), $Q_t$ is total available flow rate (m$^3$/min), L is length of each furrow (m), $N_{fs}$ is number of furrows/each irrigation set and W is width of each furrow (m).

Regarding to the fig. 1, the equation (1) to (4) including:

$$N_{sl} = \frac{L_f}{L} \tag{1}$$

$$N_{fs} = \frac{Q_t}{Q_0} \tag{2}$$

 

$$N_{sw} = \frac{W_f}{W.N_{fs}} \qquad (3)$$

$$N_s = N_{sl}.N_{sw} \qquad (4).$$

Substitution of the equation (1), (2) and (3) in the equation (4), the following equation obtains:

$$N_s = \frac{W_f.L_f.Q_o}{L.W.Q_t} \qquad (5).$$

Costs of the furrow irrigation can be divided into four parts that are explained as below:

#### 2. 1. Water Cost.

Water cost is computed by multiplying the required water volume and the price of unit volume of water ($m^3$):

$$C_{tw} = Q_t.T_{co}.N_s.C_w \qquad (6).$$

Where,

$C_{tw}$ is the cost of the required water for one time irrigation of the whole farm (Rials); $C_w$ is the price of water volume unit ($Rls/m^3$); $T_{co}$ is cut-off time (min).

By substituting the equation (5) and the equation (6), the equation (7) obtains:

$$C_{tw} = \frac{C_w.W_f.L_f.Q_0.T_{co}}{W.L} \qquad (7).$$

#### 2. 2. Workforce Cost

This cost obtains by multiplying the required time for irrigating the whole farm and the workforce cost in the unit of time as follows:

$$C_{tl} = T_{co}.N_s.C_l \qquad (8).$$

Where,

$C_{tl}$ is workforce required expense for one time irrigation of the entire farm (Rials). $C_l$ is workforce cost for unit of time (Rls/min)

By substituting the equation (5) and the equation (8), the following equation obtains:

$$C_{tl} = \frac{C_l.W_f.L_f.Q_0.T_{co}}{W.L.Q_t} \qquad (9)$$

#### 2. 3. Furrow Digging Cost

The furrow digging cost obtains by multiplying the total length of furrows and the digging cost of their length unit which concerns the whole of growing season. For one time irrigation, it must divide to the number of irrigation events:

$$C_{tf} = \frac{L_f.W_f.C_f}{N_i.W} \qquad (10)$$

where, $C_{tf}$ is cost of furrow digging for one time irrigation of the whole farm (Rials), $C_f$ is cost of digging furrow length unit (Rls/m), $N_i$ is number of irrigation events during the growing season.

The above mentioned cost is not a function of planning variables like the inflow rate and the furrow length. Therefore its value is constant and is not important in the calculation of the optimization and only involves in computing the total of the costs.

#### 2. 4. Cost of Digging the Head Ditch

According to fig. 1, for several irrigation sets, a head ditch is dug at end of upstream of furrows. Cost of these ditches computes by multiplying their total length to the digging cost of length unit. Similar to the previous section, this cost should be divided by the number of irrigation events:

$$C_{td} = \frac{W_f.N_{sl}.C_d}{N_i} \qquad (11)$$

where,

$C_{td}$ is cost of digging the irrigation streams for one time irrigation of the whole farm (Rls). $C_d$ is expense of digging the length unit of stream (Rls/m). By substituting the equation (1) and the equation (11), the following equation obtains:

$$C_{td} = \frac{W_f.N_{sl}.C_d}{L.N_i} \qquad (12)$$

Total cost for one time irrigating calculates with the following equation:

$$C_t = \frac{W_f.L_f.Q_0.T_{co}}{W.L}(C_w + \frac{C_l}{Q_t}) + \frac{W_f.L_f}{N_i}(\frac{C_f}{W} + \frac{C_d}{L}) \qquad (13)$$

where $C_t$ is total irrigation cost for one time irrigation of the farm (Rials).

An equation similar to equation (13) was proposed by Valiatzas (2001). Equation (13) indicates that the total cost depends on three variables including $Q_0$, $T_{co}$, and L. $T_{co}$ can be written as a function of the two other variables. So, the following equation obtains:

$$T_{co} = T_l + T_r \qquad (14)$$

where $T_l$ is the advance time (min), $T_r$ is intake opportunity time (min).

To compute $T_r$, any infiltration equation can be used. For the Kostiakov equation, computation is as follows:

$$Z = K.T^{\alpha} \tag{15}$$

$$T_r = (\frac{Z_r}{K})^{1/\alpha} \tag{16}$$

Where Z is depth of the percolated water (m), T is percolation time (min), $Z_r$ is net irrigation requirement (m), K and α are infiltration coefficients of the Kostiakov equation

To compute $T_1$, an explicit and precise equation should be used. So optimization of equation (13) can be done. For this purpose, the equation (17) that was proposed by Valiatzas (2001) is used:

$$T_1 = \frac{(1+0.15\alpha).L.A_0}{Q_0 + (\sigma_z.K.L/Q_0)^{1/(1-\alpha)}} \tag{17}$$

where, $A_0$ is the area of cross section at the end of upstream of the furrow ($m^2$); $\sigma_z$ is subsurface flow shape factor. This coefficient is computed from the equation (18):

$$\sigma_z = \frac{\alpha.\pi.(1-\alpha)}{Sin(\alpha.\pi)} \tag{18}$$

$A_0$ value is computed using the Manning equation and the furrow form coefficients are computed using equation (19):

$$A_0 = (\frac{N^2 Q_0{}^2}{3600 S_0.\rho_1})^{1/\rho_2} \tag{19}$$

where N is the Manning's roughness coefficient, $S_0$ is furrow bed slope (m/m), $\rho_1$ and $\rho_2$ are furrow shape coefficients. These coefficients, regarding the Manning equation are calculated as equation (20):

$$A.R^{4/3} = \rho_1 A^{\rho_2} \tag{20}$$

Where, A is flow cross section ( $m^2$ ), R is Hydraulic radius (m).

Finally through substituting the eqs. (4), (16), and (17) in the equation (13), equation (21) obtains that $C_t$ is a function of the two variables of $Q_0$ and $L_0$. This equation can be written as follows:

$$C_t = f(Q_0, L) \tag{21}$$

To compute these two variables the equation (21) should be optimized.

### 3. Findings and Discussion

The reason of using the optimization method in furrow design is firstly differentiation of the equation (21) that does not obtain the variables explicitly. Secondly, the optimization method provides the possibility for employing the numerical solution techniques using the computer. The procedure for applying this method is explained as following.

An optimization method involves the following four parts:

I. Decision variables. These variables are unknown and should be specified by the optimization.

Decision variables of the optimization model in the research are $Q_0$ and L.

II. Parameters: These variables are known. These parameters are all the variables existing in equation (21), except the decision ones. Equation (21) is combined with Eqs. 13 to 19 that having many known variables in these equations.

III. Objective function. equation (21) shows the relationship between the optimized quantities with the decision taking variables in the form of a mathematical function.

IV. Restrictions. Some of the optimization methods are restrained. Thus the decision taking variables call restrictions. In this research the following restrictions are used for the decision taking variables.

$$L > 0, Q_0 \le Q_{max}$$

In these conditions, $Q_{max}$ is the maximum inflow rate to the furrow which does not cause erosion. SCS has been proposed in the equation (22) for computing it ( $m^3$/min).

$$Q_{max} = \frac{0.00036}{S_0} \tag{22}$$

Using the above four sections, optimization is performed as following steps:

1. Primary values are assumed for the decision variables:

$$X_1 = [\begin{matrix} Q_0^{(1)} \\ L^{(1)} \end{matrix}]$$

2. An assumptive direction of $S_1 = [\begin{matrix} 0 \\ 1 \end{matrix}]$ is considered which new values for the decision variables are estimated as following:

$$X_2 = [\begin{matrix} Q_0^{(2)} \\ L^{(2)} \end{matrix}] = X_1 + \lambda_1.S_1 \tag{23}$$

3. Through placing $X_2$ in the objective function and equal its derivative to zero, $\lambda_1, \lambda_1$ are estimated and by substituting it in the equation (23), $X_2$ value is computed.

4. $X_3$ value is computed by equation (24):

$$X_3 = 2X_2 - X_1 \tag{24}$$

5. Provided $f(X_3) < f(X_2)$, the above mentioned steps are repeated. Otherwise the $S_1$ direction should be changed as follows:

$$S_1 = X_2 - X_1 \tag{25}$$

6. Computations are repeated with the new $S_1$ until the minimum point of the objective function achieve.

All the mentioned computations are performed using LINGO and finally L and Q. values and the minimum costs are computed. Then, using the equation (14) and with the following equation, the irrigation efficiency can be computed:

$$E_a = \frac{Z_r.W.L}{Q_0.T_{co}} \times 100 \tag{26}$$

In the above equation, E is the irrigation efficiency percentage.

According to the equation (13) along with minimization of $C_1$, $Q_o$. $T_{co}$ , irrigation efficiency in equation (26), will be maximized.

Briefly, the method that was explained in this paper led to calculation of inflow rate to the furrow, furrow length, irrigation duration (period) and irrigation efficiency based on expense minimization and irrigation efficiency maximization. In the other words, optimal furrow design has been obtained.

For example the following data for furrow optimized planning has been introduced into the optimization:

$Z_r$=0.1m, $Q_t$=9.48m$^3$/min,
K=0.0016, a=0.762,

$N_i$=7, n=0.04, $S_0$=0.001,

$\rho_1 = 0.3269$ , $\rho_2 = 2.734$ ,

$W_f$=100m, $L_f$=1000m,
$C_1$=60rials/min, $C_f$=100rials/m

$C_d$=200rials/m, $C_w$=20rials/m$^3$.

Results of the optimizations model are as follows:

L=100m, $Q_0$=0.0498m$^3$/min,

$T_{co}$=312min, $E_a$=48.7%

$C_t$=2450000 rials.

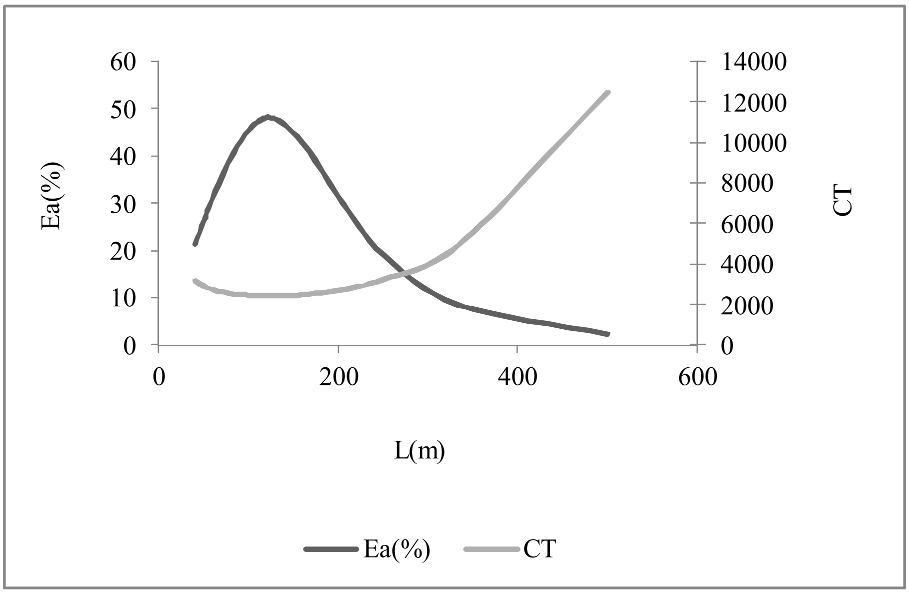


Fig. 2. Sample of cost and irrigation efficiency variations related to length of furrow

**4. Conclusion**

In the present study, the minimum irrigation cost and maximum irrigation efficiency obtain for the inflow rate of 0.0498 (m$^3$/min) and length of 100 (m) for the furrow. According to the above flow rate, by increasing or decreasing the furrow length, decrease the irrigation efficiency and increase its cost. The slope of cost and irrigation changes relative to the furrow length has optimal points that were shown in fig 2. Similarly, the slope of cost and irrigation efficiency relative to inflow rate can be drawn for a furrow in the length of 100 m. In this case through increasing or decreasing the inflow rate, irrigation cost increase and irrigation efficiency decreases.

According to the findings of Booher (1974) a furrow length of 190 m obtained which is significantly different with the present study findings.. In mentioned tables, the furrow length is a function of depth of irrigation water and bed slope of the furrow and soil texture. Other furrow properties have not been considered. According to fig 2, irrigation efficiency is 32%, for a furrow length of 190 m.

The following comments recommend:

 

The optimal furrow design curves can be drawn for variety of soils and furrows for various values of net irrigation requirements.

The issue of low irrigation can be easily inserted into this method. For this purpose it is assumed that percolation at the end of the furrow is less than the net irrigation requirement.

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