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Variation of Design Parameters in Micro-Irrigation Laterals

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Micro-irrigation laterals deliver irrigation water to the plant root zones through emitters in a micro-irrigation (drip, trickle) system. Adequate analysis of micro-irrigation laterals is very important for the design and evaluation of micro-irrigation systems. Design of a lateral pipe includes the determination of the pipe length or the inside diameter, the required operating inlet pressure head and total friction head losses along the lateral assuming that the total flow rate at the inlet, characteristic of the emitter, and the acceptable level of uniformity are known previously. In this study, the forward-step method (FSM) that takes into account to the velocity head change and variation of the Reynolds number, which affects the selection of the proper friction coefficient formula to be applied along the different reaches of the lateral pipes was presented, and then, a computer program in Visual Basic 6.0 language named LATCAD was provided for analyzing and designing of micro-irrigation laterals. This method has the highest accuracy because only the basic equations of the hydraulics of steady pipe flow were used. In this study, variation of the operating inlet pressure head, total friction head losses and uniformity coefficients depend on the pipe lengths ranging between 25 and 250 m and the internal diameters ranging between 10 and 21 mm in zero slope condition were evaluated graphically in dimensionless form for practical purposes. These presented figures could also be used as the design charts. The results of computer program based on the forward-step method are in close agreement to those obtained by other researchers.

Keywords: Irrigation system, micro-irrigation, drip (trickle) irrigation, low-volume irrigation, laterals, smooth pipe flow, lateral hydraulics, emitters, uniformity coefficient, pipeline network.

1. Introduction

Adequate analysis of micro-irrigation lateral hydraulic is very important for the design and evaluation of the irrigation systems. One of the main tasks of the lateral hydraulic calculation, is the total friction head losses determination. In addition, the variation of the emitter outflows within limited values which defined by the uniformity coefficients is important. Because it leads to a relatively short variation in the Reynolds number range, and therefore, in a short run along the Moody′s diagram. The design procedure which is based on the uniformity coefficients depending on the variation of discharge is accepted or refused. In fact, the real value of these coefficients, should be just obtained with taking into account all emitter outflows along the lateral line [1].

The hydraulic design of a lateral or a sub main unit in a micro-irrigation system has been a problem tackled by many authors. The increasing progress in computer technology has led to the development of analytical and numerical methods of hydraulic analysis as the differential method (DM), Runge-Kutta numerical method (RKM), the energy-gradient line method (EGL), and modified EGL method, the finite-element method (FEM), the forward-step method (FSM), the successive-approximations method (SAM) and others. It has an exact solution, the forward-step calculation [2] applied to accurately establish the flow characteristics and also total head losses caused by friction along the lateral line. In fact, total friction head losses for micro-irrigation laterals are determined by the forward-step method, exactly, because of the kinematic head (velocity head) is taken into consideration to obtain accurate results.

[3] introduced the widely used friction correction factor that allows direct computation of friction head loss in a lateral. The friction correction factor (F) is a function of the number of outlets and the exponent of the velocity term in the friction formula used. The friction correction factor and its subsequent improvements were developed for fixed, periodic, or linear displacement laterals. It assumes the discharge through the lateral decreases linearly with the length of the lateral. The energy line approach is traditionally used for the determination of the lateral pressure head profile [4,5]. In this analytical approach, computations are considerably simplified by assuming that the

emitter discharge is constant along the lateral. However, significant deviations from accurate numerical solutions in hydraulic analysis could be caused by this basic assumption of constant emitter outflow.

Warrick and Yitayew [6,7], presented an alternative treatment in which the emitters are considered to be close enough that the lateral can be regarded as a homogenous system of a main tube and a longitudinal slot. This treatment includes a spatially variable discharge function. It dismissed the assumption of a uniform emitter discharge along the lateral, as suggested in methods presented by Wu and Gitlin [4]. This method, however, requires the numerical solution of a nonlinear second-order differential equation (DM).They showed that the velocity head had no significant effect on micro-irrigation lateral design, and therefore assumed a hydraulically smooth flow along the lateral pipe and disregarded the laminar flow that occurs at a downstream part of the pipe. Furthermore, they disregarded the fully turbulent flow that may occur at an upstream reach of the pipe. In addition Yitayew and Warrick [8,9] presented a chart to design for trickle lateral. When the required average emitter discharge, the required uniformity of water application, and other conditions are given, a lateral length or inside diameter with operating inlet pressure head can be designed. Yitayew [10] , presented simplified approach which extension to the analytical solutions, for the determination of total friction head losses. In this approach, previously, the relative discharge values at the two boundaries (downstream and upstream end of the lateral) are computed and then total friction head losses are determined.

Hathoot et al. [2] presented a stepwise-calculation method in forward form (FSM) for analysis and design of a micro-irrigation lateral. For the method presented in their paper, a small increment of pressure head is given at the inlet of the lateral. Based on the required average emitter discharge and the required uniformity of water application, design charts similar to that presented by Yitayew and Warrick [9]was developed. In these charts, the relationship of the lateral length with uniformity coefficient and inlet pressure head and the relationship of the lateral inside diameter with uniformity coefficient and inlet pressure head for various lateral slope conditions and emitter characteristics can be calculated. This method has the highest accuracy because only the basic equations of the hydraulics of steady pipe flow were used.

Scaloppi and Allen [11], assuming constant outflow (linear total discharge variation along the lateral), derived pressure head distributions taking into account the effect of velocity head.

Kang and Nishiyama [12] developed a method for designing single lateral and paired laterals on both flat and sloped fields to meet the required average emitter discharge and the required uniformity of water application using the finite element method (FEM). In this method the minor head loss due to a fitting (an emitter connection and riser, barb, or expansion) located at any section of pipe element is taken into account therefore, the fitting loss factor is expressed as a constant independent of the discharge of the pipe element.

Following this work, Kang and Nishiyama [13] also presented the best sub-main position named "the Golden section search "is that location where the same minimum pressure exists in uphill and downhill laterals for designing of paired laterals. They used a finite-element scheme and a polynomial lateral flow rate equation, with the inlet pressure head as an independent variable, to determine pressure and flow distribution.

Valiantzas [14] presented an analytical method which modified the energy - gradient line method [4,5] for direct calculation of lateral hydraulics based on the assumption that emitter outflow is spatially variable. In this study, constant discharge and variable discharge method are compared for the nine design examples which covering various combinations of design parameters and indicated that the results of variable discharge method are more accurate than other′s results.

Anwar [15,16] developed a friction correction factor for laterals with outlets and outflow at the downstream end of lateral. He demonstrated the application of this friction correction factor to calculate friction head loss in tapered laterals. Following this work, Anwar [17], two average correction factors introduced and demonstrated how these factors can be used to calculate the inlet pressure head for fixed, periodic, or linear displacement tapered laterals.

Vallesquino and Luque-Escamilla [18]presented an alternative approach based on successive approximations scheme (SAM) for solving lateral hydraulic problems in laminar or turbulent flow. In this method minor head losses and kinematic heads are neglected and the emitter outflow is accepted as a discrete and non constant variable event by means of Taylor polynomials used to calculate flow rates along the lateral. In addition, total head losses due to friction are calculated with a non constant logarithmic friction factor which includes relative roughness of the lateral pipe. This algorithm, allows hydraulic computation for a set of connected laterals (with different pipe line diameter, slope, flow regime, or emitter spacing) if a residual outflow is used. However, total friction head losses, water application uniformity and inlet pressure head can be hard to calculate because of the requirement an excessive calculation effort.

Following this work, Vallesquino and Luque-Escamilla [19] presented an alternative approach based on the previous iterative technique using equivalent friction factor instead of the variable friction factor along lateral for predicting friction drop and outflow variation in designing single or multi-diameter sprinkler and micro-irrigation laterals. However, each step of this algorithm was clearly analyzed and discussed by Yıldırım and Ağıralioğlu [20] from important points of view. They reported that the algorithm is less efficient for predicting flow variables and it gives some deviation from the accurate numerical stepwise calculation method for different design cases.

Valiantzas [21], developed a continuously variable outflow approach considering the effect of the number of outlets. In this approach, analytical expressions for determining the inlet pressure head and global statistical parameters characterizing the outflow distribution (Christiansen uniformity coefficient, pressure head variation) are developed for design and evaluation purposes. In the latest study, Valiantzas [22]presented a new analytical approach based on the two previous basic assumptions for designing multi-diameter irrigation laterals. In these methods, analytical equations were presented for the case of obtaining general solution by the direct calculation.

Yıldırım and Ağıralioğlu [23] developed a simplified analytical approach for designing tapered two-diameter micro-irrigation laterals based on the variable outflow approach. They presented a linear solution of the simple power equation and compared it with the previous study [22] on different ground slope conditions. They reported that the linear solution yielding more accurate predictions for determining flow parameters than those of the mentioned literature for different design cases.

In the recent study, Yıldırım and Ağıralioğlu [24] analyzed and classified some lateral hydraulic design methods based on the assumption of spatial variance of emitter outflow for comparative purposes from points of view such as solution methods, basic assumptions, used formulations and differences in application [25,26]. In their study, the comparison test was applied for the seven design examples with the special limited design conditions of some calculation methods, such as emitter discharge exponent, flow regime and velocity head consideration to cover various combinations of irrigation parameters, varying emitter discharge exponents and different ground slope conditions. The results were shown graphically in dimensionless form, for practical purposes.

In this study, the forward-step method (FSM) was developed by Hathoot et al. [2] is presented. Resulting a computer program in Visual Basic 6.0 language named LATCAD is provided for analyzing and designing micro-irrigation laterals. According to the presented method, for a lateral pipe with equally spaced individual emitters and uniform slope the comparison test is extended for various combinations of irrigation design parameters. Examples will be presented for the smooth pipe case and for the most commonly used values of emitter exponent ($y = 0.2$, 0.5 and 1.0), zero slope condition ($S_0 = 0.0$), and various lengths and inside diameters of the lateral. For the sake of comparison, the design curves in dimensionless form that relate the required operating inlet pressure head, the uniformity coefficients, the total friction head losses with the lateral lengths and inside diameters were developed.

2. Principles of Lateral Hydraulics (Governing Equations)

A trickle distribution system is a hydraulic structure whose design is limited by the irrigation uniformity and consequently by the friction head losses [27]. Design of this system depends upon a good understanding of lateral hydraulics and emitter characteristics. Hydraulically, flow in the lateral pipe is considered to be a steady, spatially varied flow with decreasing emitter outflow in the downstream direction. With decreasing discharge along the lateral, the energy gradient line decreases.

Generally, emitters are usually identical, and installed at an equal spacing on the lateral line. The flow characteristics of trickle emitters are typically described by a function of the form [28,29]

$$q_n = c\ H_n^y \qquad (1)$$

in which q_n is the outflow from an individual emitter; H_n is the pressure head in the lateral pipe at the emitter under consideration; c is the emitter coefficient that accounts for areal and discharge effects and makes the units correct. For a lateral, the spacing between successive individual emitters (s), the emitter coefficient (c), and the cross-sectional area of the lateral pipe (A), are taken as constants. The emitter discharge exponent y characterizes the flow regime and emitter type. Values of y should range from zero for a pressure-compensating emitter to 1.0 for an emitter in a laminar flow regime. The value of the discharge exponent should be close to 0.5 for emitters operating in a turbulent flow regime. The higher value of the emitter discharge exponent, the greater degree of care is required to maintain the proper pressure distribution along the lateral for the same uniformity of application [30].

Let us consider the lateral stretch as shown in Fig. 1. If there are N emitters on the lateral with a common spacing S, the number of spacing will be (N-1) and the length of the lateral is the distance between the first and last emitter, L = S (N - 1).

As shown in Fig. 1, H_1 is the initial inlet pressure head, Q_1 the initial lateral discharge (Q_1 = N q_{av}) upstream from the first emitter, and q1 the outflow of the first emitter, which may be written as

$$q_1 = c\ H_1^y \qquad (2)$$

Assuming that the outflow varies continuously in space along the lateral (the number of emitters is sufficiently large), the outflow per unit length (q) can then be described by

$$q = (\frac{c}{s}) H_n^y \qquad (3)$$

If continuity is preserved along lateral, the conservation of mass is written in the general following form

$$\frac{dQ}{dx} + \frac{dA}{dt} = -q \qquad (4)$$

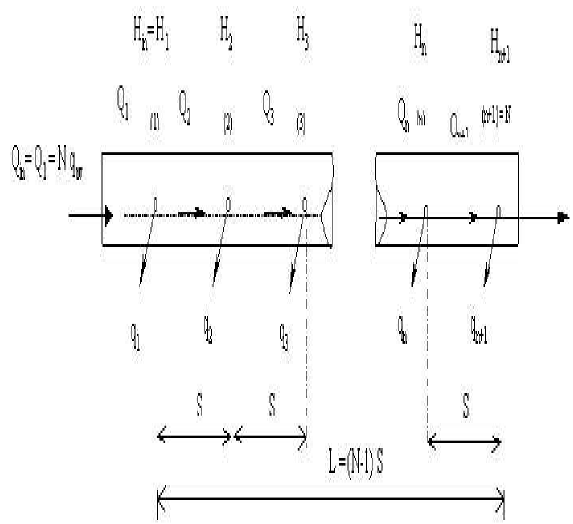

Figure 1. Lateral pipe stretch with successive multiple emitters

where Q is the lateral discharge; x and t are space and time coordinates. For steady flow condition $(\frac{dA}{dt})$=0 in irrigation laterals, the continuity equation, Eq. 4, may be rewritten as follows

$$A\frac{dv}{dx} = -q \qquad (5)$$

where v is the velocity of flow in the lateral pipe.

As shown in Fig.1, using the continuity equation, Eq. 5, the lateral discharge, Q_{n+1}, at the pipe reach between successive emitters (n) and (n+1), can be obtained from

$$Q_{n+1} = Q_n - q_n \qquad (6)$$

The lateral discharge between the first and second emitters Q_2 can be evaluated from Eq. 6 in the special form :

$$Q_2 = Q_1 - q_1 = (N\ q_{av}) - (c\ H_1^y) \qquad (7)$$

The momentum effect resulting from decreasing the discharge in downstream direction, the conservation of momentum equation is given by the following form [31]

$$\sum F = \rho(Q_{n+1}V_{n+1} - Q_nV_n) \qquad (8)$$

where $\sum$ F is the change of pressure force; ρ is the density of irrigation water; V_n and V_{n+1}

are the flow velocity between successive emitters (n-1)~(n) and (n)~(n+1), respectively.

Using the conservation of momentum equation, Eq. 8, the change of pressure head, ΔH_{n+1}, due to change of momentum between successive emitters (n) and (n+1) resulting from decreasing the discharge from Q_n to Q_{n+1}, may be written as follows

$$\Delta H_{n+1} = \frac{(Q_{n+1}^2 - Q^2 n)}{gA^2}, \tag{9}$$

where g is the acceleration due to gravity.

Watters and Keller [32] have shown that for small diameter smooth pipes used in trickle laterals, the Darcy-Weisbach friction formula can give accurate predictions for frictional losses based on conservation of energy. Therefore the following expression can be written

$$H_{fn+1} = f_{n+1} \frac{s}{D} \frac{Q_{n+1}^2}{2gA^2}, \tag{10}$$

where $Hfn+1$ is the friction head loss between successive emitters (n) and (n+1); f_{n+1} is the Darcy-Weisbach friction coefficient for the pipe reach between successive emitters (n) and (n+1); D is the internal diameter of the lateral pipe. Eq. 10 may be rewritten simplifying

$$H_{fn+1} = \frac{8S}{\pi^2 g D^5} f_{n+1} Q_{n+1}^2. \tag{11}$$

If the lateral pipe has a uniform slope S_0 , the difference in levels of points (n) and (n+1) may be given by

$$(z_n - z_{n+1}) = \pm S\ S_0, \tag{12}$$

The positive sign is for laterals sloping downward and the negative for upward slopes, z_n and z_{n+1} are elevations of successive emitters (n) and (n+1) respectively, above an arbitrary datum.

Using conservation of the energy principle with Eq. 9 and Eq. 11, between successive emitters (n) and (n+1), the following form can be obtained

$$\begin{aligned} H_n + \frac{V_n^2}{2g} + z_n \quad &= \quad H_{n+1} + \frac{V_{n+1}^2}{2g} + z_{n+1} + \\ &\quad H_{fn+1} + \Delta H_{n+1}, \end{aligned} \tag{13}$$

where H_n and H_{n+1} are pressure head for the successive emitters (n) and (n+1); $\frac{Q_n^2}{2gA^2}$ and $\frac{Q_{n+1}^2}{2gA^2}$ are velocity head under consideration.

Solving Eq. 13 for the pressure head at the emitter (n+1), H_{n+1} is related to H_n by the following equation

$$\begin{aligned} H_{n+1} \quad &= \quad H_n + \left(\frac{Q_n^2}{2gA^2}\right) - \left(\frac{Q_{n+1}^2}{2gA^2}\right) + \\ &\quad (z_n - z_{n+1}) - h_{n+1} - H_{n+1}. \end{aligned} \tag{14}$$

Combining conservation of mass and momentum principles Eq. 6 and Eq. 9 with Eq. 11 and Eq. 12, into conservation of energy principle, Eq. 14, and simplifying

$$\begin{aligned} H_{n+1} \quad &= \quad H_n + \frac{3}{2gA^2}[Q_n^2 - (Q_n - q_n)^2] - \\ &\quad f_{n+1} \frac{8S}{\pi^2 g D^5}(Q_n - q_n)^2 \pm S\ S_0. \end{aligned} \tag{15}$$

For convenience, Eq. 15 is put in the form

$$\begin{aligned} H_{n+1} \quad &= \quad H_n + B[Q_n^2 - (Q_n - q_n)^2] - \\ &\quad E f_{n+1}(Q_n - q_n)^2 \pm S\ S_0 \end{aligned} \tag{16}$$

in which

$$B = \frac{3}{2gA^2} \tag{17}$$

and

$$E = \frac{8S}{\pi^2 g D^5}\ . \tag{18}$$

As seen from the above hydraulic analysis, there are four basic equations in the lateral hydraulics. These equations are: 1. the emitter discharge-pressure head relationship as Eq. 1, 2. the continuity equation as Eq. 5, 3. the Darcy-Weisbach friction formula as Eq. (10), 4. the conservation of energy equation coupled with the conservation of momentum equation as Eq. 13. On the other hand, there are four unknown hydraulic variables (Q_{n+1}, q_{n+1}, H_{n+1} and H_{fn+1}) at any location of lateral (n+1), with the known previous values (Q_n, q_n, and H_n), and the other parameters (z_n, z_{n+1}, f_{n+1}, D, s, c and y). These unknown variables can be estimated using some calculation method.

2.1. Water Application Uniformity

One of the main tasks of the lateral hydraulic calculation is to provide a sensitive balance between the inlet pressure head, the water application uniformity, and the total frictional losses along lateral. In designing laterals, the variation of the emitter discharge within limited values, which are defined in the uniformity coefficients, namely the Christiansen's uniformity coefficient (UC) and the lower-quarter distribution uniformity coefficient (DU_{LQ}), is important, because it leads to a relatively short variation in the Reynolds number range, and therefore, in a short run along the Moody's diagram. The design procedure, which is based on the uniformity coefficients depending on the variation of emitter discharge, is accepted or refused. In fact, the real value of these coefficients should be obtained by taking into account all emitter discharges along the lateral line [33].

Obviously, individual emitters are convenient to consider expressions for emission uniformity, which is the relationship between the minimum and average emitter discharge within the system [34]. The Christiansen's uniformity coefficient and the lower-quarter distribution uniformity are used here to express uniformity of emitter discharge throughout the system. DU_{LQ} is defined as the average discharge for the lower-quarter of the lateral divided by the overall average q_{av} [9]

$$UC = 1 - \frac{1}{Nq_{av}} \sum_{n=1}^{n=N} |q_n - q_{av}| \tag{19}$$

and

$$DU_{LQ} = \frac{4 \times \left[\sum_{n=\frac{3N}{4}}^{n=N} (q_{low})_n\right]}{N \times q_{av}} \tag{20}$$

where ; q_{av} : average emitter discharge along the lateral pipe; q_n: discharge of emitter (n) and $(q_{low})_n$: discharge of the lower-quarter emitter n = 3N/4.

The uniformity of water application can also be evaluated using the emitter flow variation (V_{HM}). V_{HM} is defined by [35,36]

$$(V_{HM}) = (V_H^2 + V_M^2)^{1/2} \tag{21}$$

where V_H = effective pressure head variation at the emitters; and V_M = manufacturing variation of emitters.

2.2. Coefficient of Friction

Micro-irrigation laterals are generally made of smooth materials. Flow in laterals is generally turbulent : $3000 < R = 10^5$, sometimes fully turbulent flow : $10^5 < R < 10^7$, exists at the upstream end of the lateral and flow becomes laminar at the downstream reach where the velocity decreases to zero. For laminar flow : $R < 2000$, the friction coefficient is given [2,9]

$$f = \frac{64}{R} = \frac{64\nu}{VD} \quad \left(R = \frac{VD}{v}\right) \tag{22}$$

or

$$f_n = \frac{16\pi\nu}{Q_n} \tag{23}$$

in which R : the Reynolds number and ν : the kinematic viscosity of water.

For turbulent flow : $3000 < R \leq 10^5$, the Blasius equation can be used :

$$f = 0.316 R^{-0.25} \tag{24}$$

or

$$f_n = 0.316 \left(\frac{\pi D\nu}{4Q_{ni}}\right)^{0.25} \tag{25}$$

For fully turbulent flow : $10^5 < R < 10^7$, we have

$$f = 0.130 R^{-0.172} \tag{26}$$

or

$$f_n = 0.130 \left(\frac{\pi D\nu}{4Q_n}\right)^{0.172} \tag{27}$$

3. Computer Program

A flowchart for LATCAD, as given in Fig. 2, can be used to evaluate the flow characteristics along the lateral pipe and the corresponding uniformity coefficients. In practice the average emitter discharge q_{av}, the corresponding pressure head H_{av}, the flow exponent y, the number of emitters n , the spacing between emitters S, and the slope S_0 and inside diameter of the lateral pipe D are assigned in advance for a certain design. The following algorithm is taken into account in designing of the computer program:

1. The initial pressure head H_{max} is first assumed by adding a reasonable head increment Δ_0 to the average head H_{av} (Initial condition).
2. The outflow of individual emitters q_i is evaluated stepwise starting from the first emitter, and in each step the corresponding lateral discharge Q_i is evaluated.
3. At each step the Reynolds number is calculated and the proper friction coefficient formula is used to evaluate the head loss due to friction and therefore the new pressure head by applying Eq. 16.

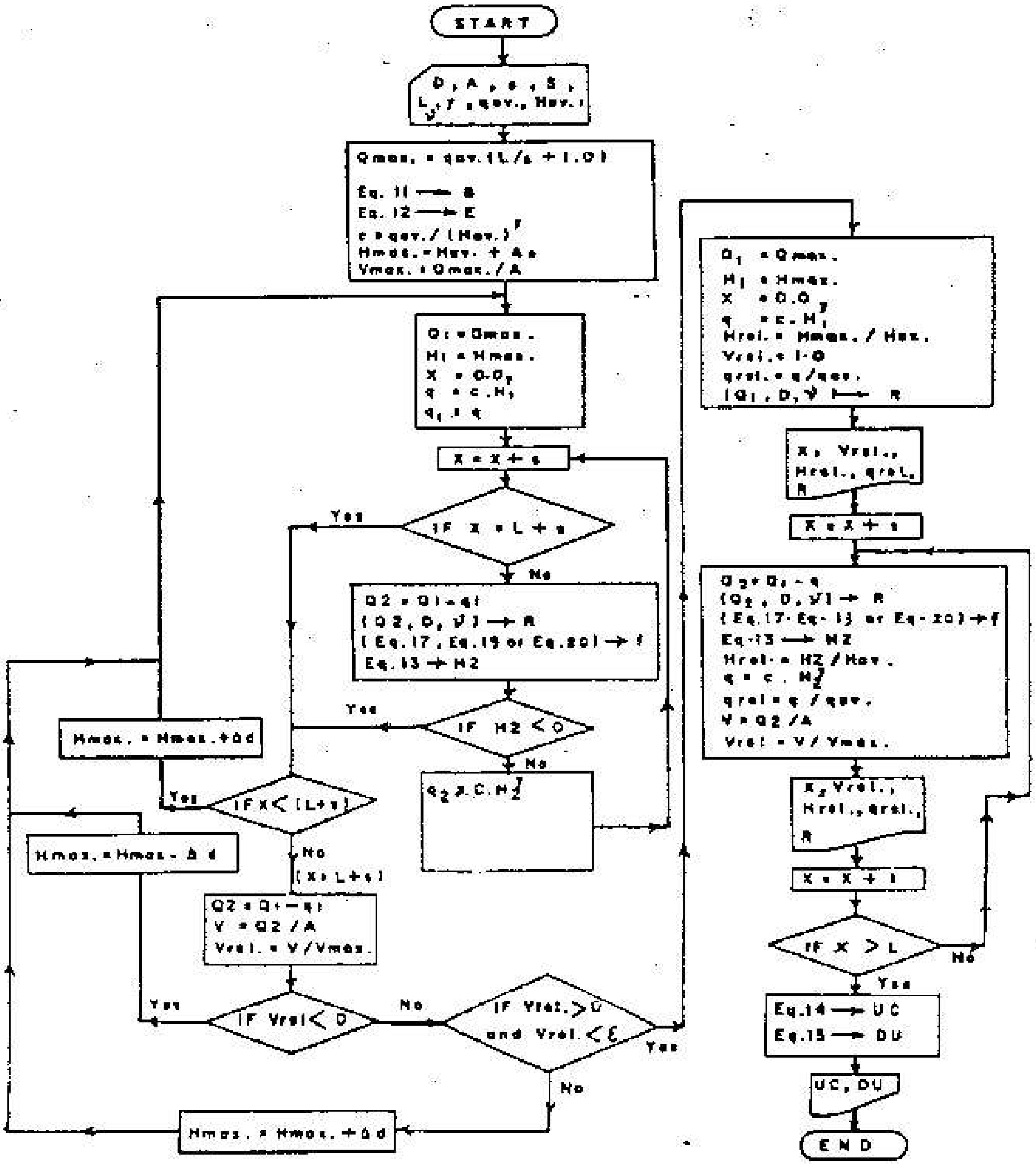

Figure 2. Flowchart for computer program.

4. If Eq. 16 yields negative values of H at any emitter, this would indicate that the assumed H_{max} should be increased by Δ_d (Boundary condition).

5. As negative values of H disappear, other conditions should be fulfilled.

6. The velocity at any reach of the lateral pipe should be positive (Boundary condition); otherwise, this would indicate that the sum of emitter outflows is greater than the initial discharge Q_{max}, which means that H_{max} should be decreased by Δ_d (Δ_d, being divided periodically by 10 on increasing or decreasing H_{max}).

7. The discharge in the lateral pipe downstream from the last emitter should be zero, which forms an important boundary condition.

8. Practically, this condition is satisfied if the relative velocity at that part becomes less than a sufficiently small quantity, ε .

9. As the proper value of H_{max} is reached, outflow, pressure head for each emitter, and the velocity at the corresponding reach of the lateral pipe are evaluated.

10. Finally, uniformity of the system is evaluated by computing UC and DU_{LQ} as given by Eq. 19 and Eq. 20 , respectively.

4. Evaluation of Design Procedure

Design procedures for a lateral pipe can be ordered in the following four steps generally [12]:

1. To give a series of values for the design parameter from smallest to largest.
2. To find the required operating inlet pressure head (H_{in}) that can create the required average emitter discharge, and to evaluate the total friction head losses and the uniformity of water application for each given value.
3. To plot the curves of the uniformity of water application, the required operating inlet pressure head and the total friction head losses versus the design parameter.
4. To find the solutions of the design parameter the required operating inlet pressure head and the total friction head losses from the curves plotted in the third step according to the required uniformity of water application.

5. Determination of the Proper Inlet Pressure Head

As seen from the above considerations, an important objective of this analysis is the proper inlet pressure head determination which can be varied within limited values in the design algorithms (boundary conditions). It means, preliminary increase in average piezometric head (Δ_0) varies ranging from minimum inlet pressure head toward maximum inlet pressure head. The design phases as follows [37]:

1. Determine inlet pressure head ranges (A, B) where inlet pressure head is located in. In (A, B), A : minimum inlet pressure head and B : maximum inlet pressure head.

a. Obtain minimum inlet pressure head, according to the 1. and 4. steps in the design algorithms (for H_1, if the smaller values than A are design, this would indicate that the negative value of the pressure head at any emitter would be appeared).

b. Obtain maximum inlet pressure head, according to the 1. and 5. steps in the design algorithms (for H_1, if the larger values than B are design, this would indicate that the sum of emitter outflows is greater than the initial lateral discharge Q_1, which means that, back flow occurs from downstream end toward upstream direction of lateral).

2. As the proper values of the inlet pressure head ($A \leq H_1 \leq B$) are obtained, the favorable value of H_1 should be investigated. In line with this concept, these following considerations should be taken into account:

a. For H_1, if A is selected for designing a lateral, the value of residual lateral discharge at the downstream end from the last emitter larger than acceptable small quantity, ε, either zero. Obviously, an important boundary condition doesn′t keep to the right by the 5. step in the design algorithms. Whereas, the residual lateral discharge decreases from A toward B, increasingly, and then for B, it has a sufficiently small value, approximately zero.

b. In designing of a lateral, the design parameters should be determined in order to minimize of total friction drop at the end of lateral. In this respect, if A is selected, the total friction drop have major values and then, from A toward B, have minor values, increasingly. However, if B is selected the total friction head losses are minimized.

c. In the design procedure, the water application uniformity is unknown parameter; other parameter (inlet pressure head) should be varied have the highest level of uniformity. Obviously, water application uniformity increases from A toward B, and then for B it has the highest value. As a result, the proper inlet pressure head is reached at B, total friction drop and residual flow rate are minimized whereas the water application uniformity is maximized.

6. Design Examples

In designing of the lateral pipe for a micro-irrigation system it is also assumed that the emitter outflow-pressure head relationship, average flow rate and characteristic of the emitter and acceptable level of uniformity are known a priori. It often remains to design either the pipe length or the inside diameter, the total discharge at the inlet, the pressure head at the inlet of lateral, the head loss due to friction along the lateral with the other variables known. The following are two design examples based on each concept.

7. Example 1. Design of Lateral Length, Inlet Pressure Head and Total Friction Losses Using Design Curves

It is given that the emitter outflow-pressure head relationship : q = $3.58\ 10^{-7}\ H^{0.5}$, average flow rate of emitter: q_{av} = 4 lh^{-1} ($1.111\ 10^{-6}$ m^3s^{-1}), spacing between successive interior emitters:S = 1.0 m, design uniformity coefficient: UC = 0.95, the inside diameter of lateral: D = 14 mm, the kinematic viscosity of water at 20°C $\nu = 1.01\ 10^{-6}$ m^2s^{-1}.

The values that must be determined are : (1) Length of lateral, (2) the pressure head at the lateral inlet, (3) the frictional head loss along lateral.

8. Solution

On the basis of the forward-step method discussed, the values of the inlet pressure H_{in} , the frictional head loss H_f and the uniformity coefficients UC, DU_{LQ} are evaluated for various pipe lengths ranging between 25 and 250 m (D = 0.014 m). In each calculation the values of design parameters are obtained from output of LATCAD and plotted in dimensionless form for practical purpose which could also be used as a design chart (Fig. 3.a, 3.b, 3.c, 3.d).

From Fig. 3.b and for design uniformity coefficient UC = 0.95; length of the lateral, L = 125 m is found. On the other hand, from

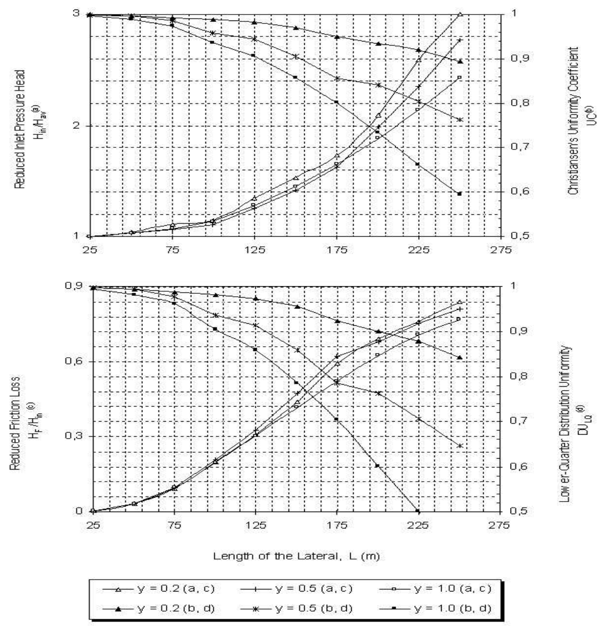

Figure 3. (a,b) Variation of Reduced Inlet Pressure Head and Christiansen′s Uniformity Coefficient with Lateral Length, (c,d) Variation of Reduced Friction Loss and Lower-Quarter Distribution Uniformity with Lateral Length

Fig. 3.a and for L = 125 m; we have relative pressure head at the inlet, H_{in}/H_{av} = 1.26. From the emitter outflow-pressure head relationship we find,

$$H_{av} = \left(\frac{q_{av}}{c}\right)^{\frac{1}{y}} = \left(\frac{1.111\times10^{-6}}{3.58\times10^{-7}}\right)^{\frac{1}{0.5}} = 9.631\ m \qquad (28)$$

Resulting ; H_{in} = 1.26 9.631 = 12.135 m is found.

From Fig. 3.c and for L = 125 m; we have relative friction drop, H_f/H_{in} = 0.326 and then the frictional head loss along the lateral, H_f = 0.326 12.135 = 3.956 m is found. For the second uniformity design parameter DU_{LQ} , from Fig. 3.d and for L = 125 m ; DU_{LQ} = 0.915 is found.

The same example was solved by [7] using differential method based on numerical solution of a nonlinear second-order differential equation and also more accurate analytical forward-step method developed by Hathoot et al. [2]. The results were presented here for the sake of comparison. Differential method gives L = 126 m, H_{in} = 12.49 m, H_f = 3.841 m and DU_{LQ} = 0.925 whereas Yitayew′s [10] head loss equation which extension of the basic analytical solution gives L = 125 m, H_{in} = 12.536 m and H_f = 3.883 m. However, Hathoot et al. [2] give L = 129 m, and H_{in} = 12.69 m. The difference between two basic solution may be attributed to this cause : In the FSM variation of the Reynolds number along the lateral pipe is considered whereas in DM the Blasius equation is used along of full lateral also including the last downstream length at the end of lateral in which flow is actually laminar. It is worthy to note that the results of computer program are in close agreement with those of other researcher′s.

9. Example 2. Design of Lateral Inside Diameter, Inlet Pressure Head and Total Friction Losses Using Design Curves

Design the following parameters for design uniformity coefficient UC = 0.95 and the lateral length L = 150 m using the same data given in Example 1.

(1) the inside diameter of the lateral, (2) the pressure head at the lateral inlet, (3) the frictional head loss along lateral.

10. Solution

The values of the inlet pressure H_{in} , the frictional head loss H_f and the uniformity coefficients UC, DU_{LQ} are evaluated for various pipe internal diameters ranging between 10 mm and 21 mm (L = 150 m). In each calculation the values of design parameters are obtained from output of LATCAD and plotted in dimensionless form for practical purpose which could also be used as a design chart (Fig. 4.a, 4.b, 4.c, 4.d).

From Fig. 4.b and for design UC = 0.95; inside diameter of the lateral, D = 16.4 mm is found. On the other hand, from Fig. 4.a and for D = 16.4 mm; we have relative pressure head at the inlet, H_{in}/H_{av} = 1.195. From the emitter outflow-pressure head relationship we find,

$$H_{av} = \left(\frac{q_{av}}{c}\right)^{\frac{1}{y}} = \left(\frac{1.111 \times 10^{-6}}{3.58 \times 10^{-7}}\right)^{\frac{1}{0.5}} = 9.631\ m \qquad (29)$$

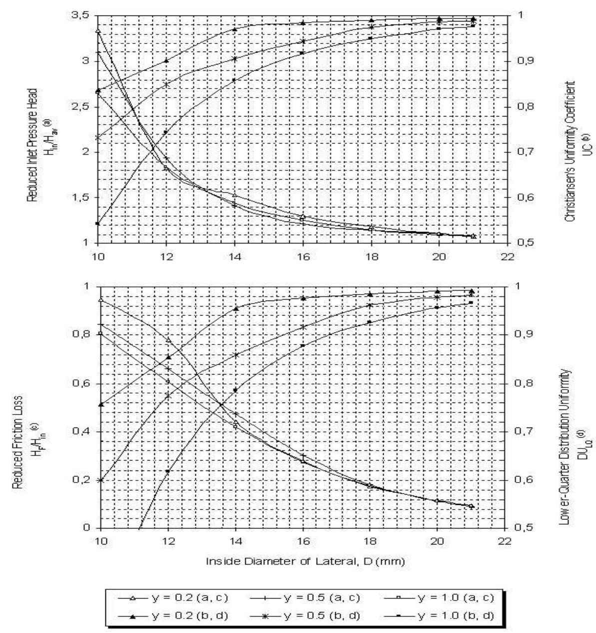

Figure 4. (a, b) Variation of Reduced Inlet Pressure Head and Christiansen′s Uniformity Coefficient with Lateral Inside Diameter, (c, d) Variation of Reduced Friction Loss and Lower-Quarter Distribution Uniformity with Lateral Inside Diameter

Resulting ; H_{in} = 1.195 9.631 = 11.51 m is found.

From Fig. 4.c and for D = 16.4 mm ; we have relative friction drop, H_f/H_{in} = 0.277 and then the frictional head loss along the lateral, H_f = 0.277×11.51 = 3.188 m is found. For the second uniformity design parameter DU_{LQ}, from Fig. 4.d and for D = 16.4 mm; DU_{LQ} = 0.925 is found.

11. Summary and Conclusions

A lateral is a hydraulic structure whose design is limited by the irrigation uniformity, and consequently, by the friction head losses. These facts is very important because it should be provided that the variation of the emitter outflows within a limited values which are defined uniformity coefficients. In addition, head loss due to friction at the end of lateral should be estimated, correctly.

In this study the principles of micro-irrigation lateral hydraulic based on the forward-step method was presented and a computer program was developed for this purpose. In this method, the design of the lateral pipe with equally spaced individual emitters and uniform slope is aimed so that hydraulic criteria are suitable and the uniformity coefficient is desired. In designing of a lateral by computer program, for a lateral length and inside diameter, firstly, the inlet pressure head is appointed, and then the friction drop along lateral and level of uniformity of the system are determined.

On the other hand, effects of design parameters on discharge distribution for consistent designing due to various combinations of the lateral length and the inside diameter can be experienced. In addition, hydraulic design criteria for lateral pipes in detail are presented. The design examples for verification the design criteria are also presented. Results obtained from covering various combinations of irrigation design parameters are plotted for three emitter characteristics and zero-slope condition graphically in dimensionless form for practical purposes. These presented figures could also be used as the design charts. For different design applications, the results of computer program based on the forward-step method has the higher accuracy and sensitivity rather than the results of other analytical and numerical methods, because only the basic equations of the hydraulics of steady pipe flow were used in each part of lateral which divided by the emitters.

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