NUMERICAL DESIGN PROCEDURE FOR MICRO-IRRIGATION MANIFOLDS

Gary P. Merkley[1]

ABSTRACT

A completely numerical design procedure for micro-irrigation manifolds was developed based on a variation of the hydraulic grade line method. The procedure determines pipe diameters and lengths for telescoping manifolds to minimize pressure variations and improve discharge uniformity. A computer program which implements the procedure is a free download from a web site. The software can accommodate a list of available pipe diameters and other parameters and options to constrain the design results within feasible limits, and it produces a graphical display of the design.

INTRODUCTION

Micro-irrigation laterals in most agricultural irrigation systems are connected to manifold pipes, and sometimes to headers which are in turn connected to the manifolds. The manifolds are sometimes thought of as sub-mains, and a primary design objective is that pressure variation along the manifolds is minimal (within reason) so that lateral inlet pressures are relatively constant, thereby providing better hydraulic performance of the system and better irrigation water management. Micro-irrigation laterals are most often of a single diameter, but manifolds may have several diameters, tapering down from larger to smaller pipe sizes.

There are various design approaches for manifold pipe sizing, including maximum velocity, hydraulic grade line (HGL), economic analysis, and others (Keller and Bliesner 1990). With the HGL method, up to four different pipe sizes are used along the manifold in an attempt to minimize pressure variation from the inlet to the downstream end. Pipe sizes (diameters) are selected from a list of available diameters such that the composite friction-loss curve closely approximates the slope of the ground surface in downhill-oriented manifolds. The HGL method has been applied in a semi-graphical form in the past, but in this paper it is shown how it can be applied through a completely numerical process, and implemented in a computer program.

SIZING OF MANIFOLD PIPES BY THE HGL METHOD

Along a micro-irrigation mainline pipe, there may be a combination of uphill and downhill portions of the manifold, thereby helping to balance pressures and provide less overall pressure variation. A combination of uphill and downhill manifold portions is often technically feasible when the average ground slope along the manifold is less than about 3%. In order to balance upstream and downstream pressures, it is always necessary for the downhill side of the manifold to be longer than the uphill side, except when the

[1] Professor, Civil and Environmental Engineering. Dept., Utah State Univ., Logan, UT, 84322; gary.merkley@usu.edu

ground slope is zero (in which case it is intuitive that the balance is achieved by having equal manifold lengths to either side of the mainline). When the average ground slope is above 3%, it is usually best to have only downhill manifolds because the uphill portion would be impractically short in length.

Uphill Side of the Manifold

On pipes running uphill, elevation change and friction loss combine to reduce pressure in the downstream direction. Thus, where there is an uphill portion of the manifold, it is best to determine the smallest allowable pipe diameter and use only the one diameter for this part of the manifold. The smallest allowable diameter is that which will provide the required lateral inlet pressure at the uphill end of the manifold, given a mainline pressure which is determined according to the design of the downhill portion of the manifold, as described below. This means that the available inlet pressure to most of the laterals on the uphill portion of the manifold will be higher than required, and throttling valves may be used to reduce this excess pressure at the lateral inlets. A different approach is to select the size of the uphill manifold pipe such that the average pressure is equal to the required lateral inlet pressure. In any case, it is also necessary to account for estimated local hydraulic losses at the point of connection of the laterals to the manifold. In the following, the length of the uphill portion of the manifold is given as x_u.

Downhill Side of the Manifold

This is the most complex part of the manifold design process, and it involves several steps, culminating in the development of a set of non-linear algebraic equations which must be solved iteratively for each pipe size to be included in the manifold. The length of the downhill portion of the manifold is represented herein by the variable x_d. The flow rate at the inlet to the downhill portion of the manifold is denoted as Q_m. The allowable pressure head variation in the manifold is defined as $(\Delta h_m)_a$, which is based on previous design calculations, taking into account a target emission uniformity (EU) and other parameters, including the lateral length and sizing. The allowable pressure head variation and the average ground slope, S_o, define an envelope within which the friction-loss curves must be confined, thereby achieving the target EU. This envelope is defined by a line representing S_o and a parallel line with a vertical offset of $(\Delta h_m)_a$ (Fig. 1).

Largest Pipe Size The largest pipe size will, of course, be at the connection to the mainline where the manifold flow rate is highest. This pipe diameter is represented as D_1. First, determine the minimum acceptable pipe diameter for the first section of the downhill side of the manifold. This can be accomplished by finding the inside pipe diameter, D, that will give a friction loss curve tangent to the ground slope (Fig. 1). To do this, it is necessary to:

(1) have the slope of the friction loss curve equal to S_o; and,
(2) have the "h" values equal at this location (make them just touch at a point).

where S_o is the average ground slope along the manifold; and, H is the pressure head in the manifold. The elevation change along the downhill portion of the manifold is ΔE_m, as shown in Fig. 1, and is equal to $S_o x_d$.

These two requirements can be satisfied by applying two equations, whereby the two unknowns will be the flow rate, Q, and the inside diameter, D_1. Here, it is assumed that the lateral inflow rate, Q_l, is constant along the length of the manifold.

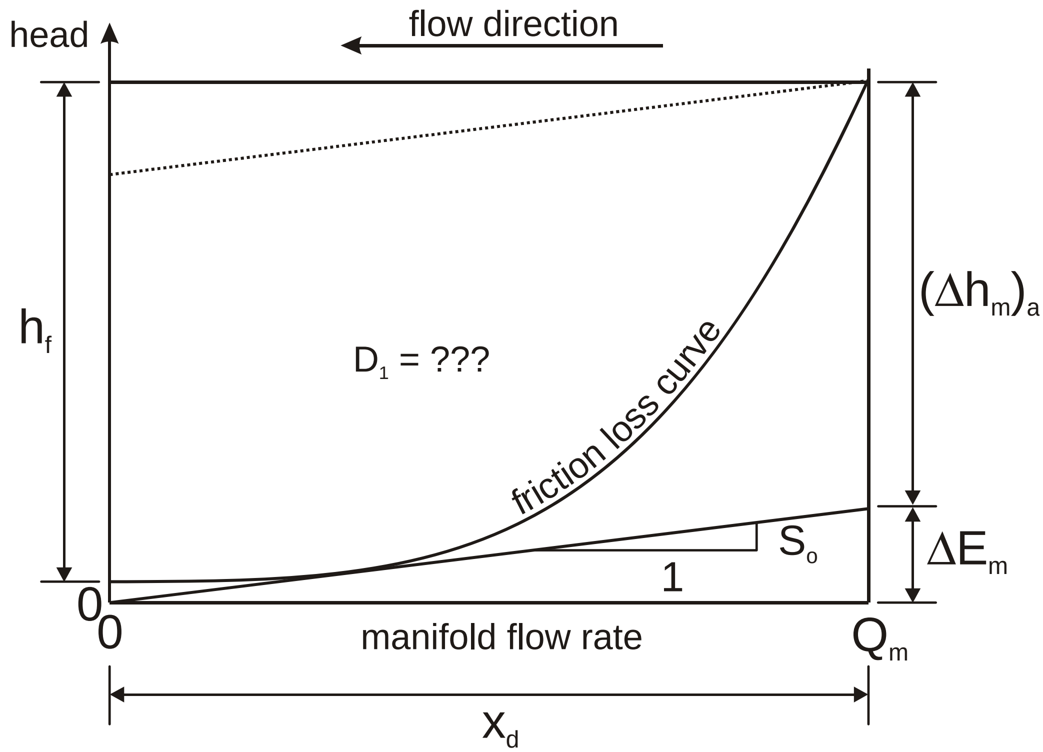

Figure 1. Schematic diagram of the friction-loss envelope for manifold pipe sizing.

In Fig. 1, where the right side is the mainline location and the left side is the downstream closed end of the manifold, the manifold flow rate varies from Q_m to zero, and the friction loss curve is defined as:

$$h = \underbrace{(\Delta h_m)_a + \Delta E_m - h_f}_{\text{constants}} + \underbrace{\frac{JFL}{100}}_{\text{varies with distance}} \quad (1)$$

where, $0 \leq L \leq x_d$. So, when L = 0, h equals the first three terms of Eq. 1, and the calculations move upstream as L increases. Using the Hazen-Williams (Brater and King 1976) pipe friction-loss equation,

$$J = K\left(\frac{Q}{C}\right)^{1.852} D^{-4.87} \quad \text{for} \quad 0 \le Q \le Q_m \tag{2}$$

$$F = \frac{1}{2.852} + \frac{1}{2N} + \frac{\sqrt{0.852}}{6N^2} \tag{3}$$

$$N = \left(\frac{x_d}{S_l}\right)\left(\frac{Q}{Q_m}\right) \quad \text{for} \quad N > 0 \tag{4}$$

where F is a factor for multiple-outlet pipes (Keller and Bliesner 1990); and, N is the number of outlets (laterals) from the location of Q in the manifold to the downhill closed end. The length to be used in Eq. 1 is:

$$L = x_d\left(\frac{Q}{Q_m}\right) \tag{5}$$

The total friction head loss in the downhill side of the manifold is:

$$h_f = \frac{J_{hf}F_{hf}x_d}{100} = 0.01K\left(\frac{Q_m}{C}\right)^{1.852} D^{-4.87}F_{hf}x_d \tag{6}$$

where F_{hf} is defined as F above, except with $N = x_d/S_l$. For Q in lps and D in cm, $K = 16.42(10)^6$.

The slope of the friction-loss curve is (applying the "chain rule" of calculus):

$$\frac{dh}{dQ} = \frac{1}{100}\left(FL\frac{dJ}{dQ} + JL\frac{dF}{dQ} + JF\frac{dL}{dQ}\right) \tag{7}$$

where,

$$\frac{dJ}{dQ} = \frac{1.852KQ^{0.852}}{C^{1.852}D^{4.87}} \tag{8}$$

$$\frac{dF}{dQ} = -\frac{x_d}{S_l Q_m N^2}\left(\frac{1}{2} + \frac{\sqrt{0.852}}{3N}\right) \tag{9}$$

$$\frac{dL}{dQ} = \frac{x_d}{Q_m} \tag{10}$$

Here it is noted that dh/dQ ≠ J. Also, the ground surface (assuming a constant ground slope, S_o) is defined by:

$$h = S_o L = S_o x_d \left(\frac{Q}{Q_m} \right) \tag{11}$$

and,

$$\frac{dh}{dQ} = \frac{S_o x_d}{Q_m} \tag{12}$$

Combine the two equations defining h (Eqs. 1 and 11), effectively causing the friction loss curve to just touch the ground surface line:

$$S_o x_d \left(\frac{Q}{Q_m} \right) = \left(\Delta h_m \right)_a + \Delta E_m - h_f + \frac{JFL}{100} \tag{13}$$

Solve Eq. 13 for the pipe inside diameter, D:

$$D = \left[\frac{100\, C^{1.852} \left(\frac{S_o x_d Q}{Q_m} - \left(\Delta h_m \right)_a - \Delta E_m \right)}{K \left(Q^{1.852} FL - Q_m^{1.852} F_{hf} x_d \right)} \right]^{-0.205} \tag{14}$$

Then, set the slope of the friction loss curve equal to $S_o x_d / Q_m$:

$$\frac{S_o x_d}{Q_m} = \frac{1}{100} \left(FL \frac{dJ}{dQ} + JL \frac{dF}{dQ} + JF \frac{dL}{dQ} \right) \tag{15}$$

Combine Eqs. 14 & 15 so that the only unknown is Q (note that D appears in the J and dJ/dQ terms of Eq.). Based on the assumption of constant lateral inflow rate, Q_m is a known value. Solve for Q by iteration. The required pipe inside diameter, D, will be known as part of the solution for Q. The calculated value of D is the minimum inside pipe diameter, so find the nearest available pipe size that is larger than or equal to D:

$$D_1 \geq D \quad \& \quad \text{minimize}(D_1 - D) \tag{16}$$

Slope of the Tangent Line Next, calculate the equation of the line through the origin and tangent to the friction loss curve for D_1. Let S_t be the slope of the tangent line:

$$h = S_t L = S_t x_d \left(\frac{Q}{Q_m} \right) \tag{17}$$

then,

$$S_t x_d \left(\frac{Q}{Q_m} \right) = \left(\Delta h_m \right)_a + \Delta E_l - h_f + \frac{JFL}{100} \tag{18}$$

Set the slope of the friction loss curve equal to $S_t x_d / Q_m$:

$$\frac{S_t x_d}{Q_m} = \frac{1}{100} \left(FL \frac{dJ}{dQ} + JL \frac{dF}{dQ} + JF \frac{dL}{dQ} \right) \tag{19}$$

Combine the above two equations to eliminate S_t, and solve for Q. Calculate the slope, S_t, directly.

Smaller (Downstream) Pipe Sizes Then take the next smaller pipe size, D_2, and make its friction loss curve tangent to the same line (slope = S_t):

$$h = h_0 + \frac{JFL}{100} \tag{20}$$

where H_0 is a vertical offset to make the friction-loss curve tangent to the S_t line, emanating from the origin. Equating heads and solving for h_0,

$$h_0 = S_t x_d \left(\frac{Q}{Q_m} \right) - \frac{JFL}{100} \tag{21}$$

Again, set the slope of the friction loss curve equal to S_t:

$$\frac{S_t x_d}{Q_m} = \frac{1}{100} \left(FL \frac{dJ}{dQ} + JL \frac{dF}{dQ} + JF \frac{dL}{dQ} \right) \tag{22}$$

Solve the above equation for Q, then solve directly for h_0. This gives the equation for the next manifold friction-loss curve. Determine the intersection with the D_1 friction loss curve to set the length for size D_1; this is done by equating the h values for the respective equations and solving for Q at the intersection:

$$h_{big} - h_{small} + \frac{FLK}{100}\left(\frac{Q}{C}\right)^{1.852}\left(D_{big}^{-4.87} - D_{small}^{-4.87}\right) = 0 \tag{23}$$

where, for the first pipe size (D_1):

$$h_{big} = \left(\Delta h_m\right)_a + \Delta E_l - h_f \tag{24}$$

and for the second pipe size (D_2):

$$h_{small} = h_0 \tag{25}$$

and F & L are as defined in Eqs. 3 to 5. Then, the length of pipe D_1 is equal to:

$$L_{D1} = x_d\left(1 - \frac{Q}{Q_m}\right) \tag{26}$$

Continue this process until there are three or four manifold pipe sizes, or until arriving at a pipe size that has $D < ½D_1$.

Figures 2 and 3 show images from a computer program (using sample data) which applies the fully numerical HGL method for manifold pipe sizing. The computer program which applies this manifold design methodology based on the Hazen-Williams equation can be downloaded at www.neng.usu.edu/bie/faculty/merkley/BIE6110.htm.

SUMMARY AND CONCLUSIONS

A completely numerical HGL design methodology was developed for pipe sizing in micro-irrigation manifolds, and was implemented in a computer program with tabular and graphical results. The methodology provides for relatively uniform pressure along the downhill portion of a manifold by selecting the most appropriate pipe diameters and lengths, thereby resulting in the achievement of relatively high emission uniformity from the irrigation system.

The above equation development can also be done using the Darcy-Weisbach pipe friction-loss equation. It is necessary to specify a minimum length for each pipe size in the manifold so that the design is feasible. For example, the minimum allowable pipe length might be $5S_l$. The friction loss curves must be shifted vertically upward to provide the correct average (or minimum, if pressure regulators are used) pressure in the manifold; this shifting process determines the required manifold inlet pressure head, h_m.

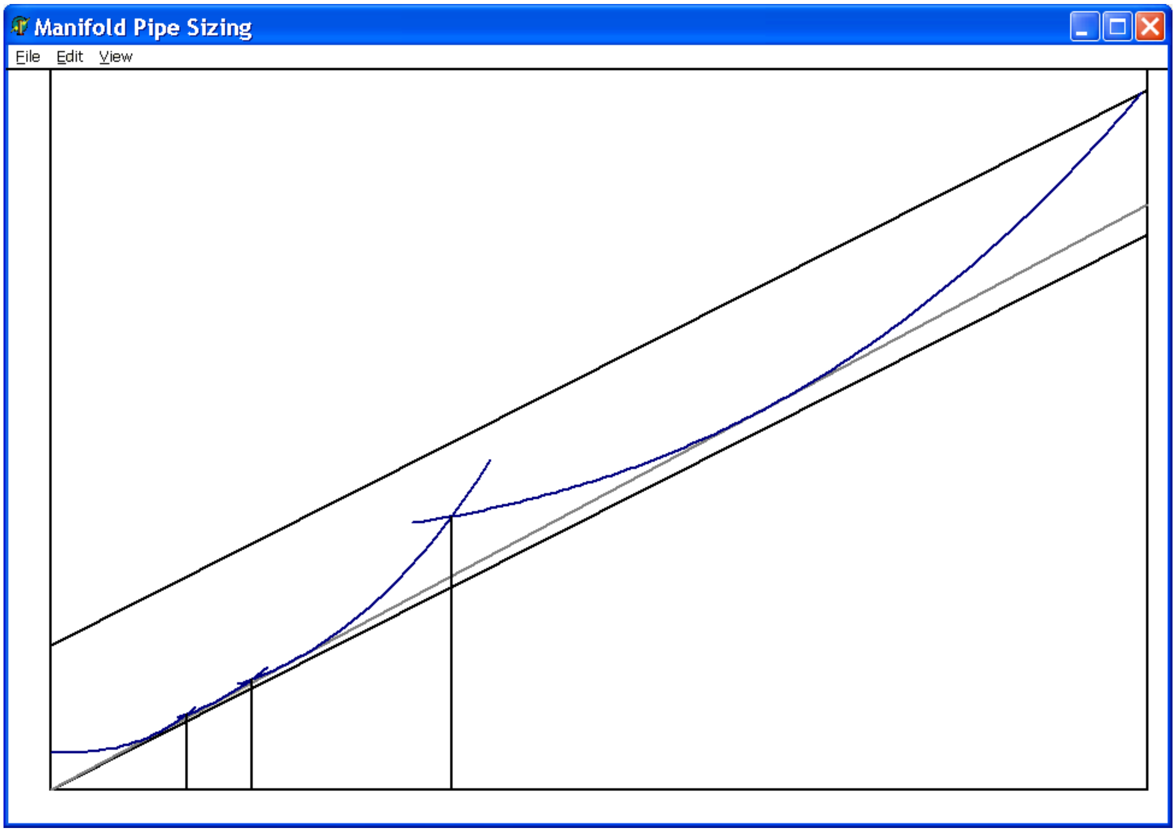

Figure 2. Schematic display of a manifold design solution from a computer program.

Manifold Pipe Sizing

File Edit View

Minimum pipe diameter= 5.9116 cm

i	index	ID (cm)	EndQ (lps)	L (m)	H0 (m)
1	6	6.0	2.195	161.72	3.41
2	5	4.0	1.101	46.47	1.14
3	4	3.5	0.742	15.26	0.79
4	3	3.0	0.000	31.55	0.51

Total length= 255.00 m

Figure 3. Tabular results of a manifold design program in a computer program.

REFERENCES

Brater, E.F., King, H.W. 1976. Handbook of Hydraulics. 6th Ed. McGraw-Hill Book Co., New York, NY.

Keller, J, Bliesner, R.D. 1990. Sprinkle and Trickle Irrigation. Van Nostrand Reinhold, New York, NY. Currently available from Keller-Bliesner, LLC, Logan, UT. 651 pp.