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Hydraulics of IDEal Drip Irrigation Systems

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HYDRAULICS OF IDEAL DRIP IRRIGATION SYSTEMS

by

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ABSTRACT

Hydraulics of IDEal Drip Irrigation Systems

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The hydraulics of IDEal drip irrigation system components were analyzed under controlled laboratory conditions and the results can be applied to the design of IDEal systems. The hydraulic loss coefficient for the lateral-submain connector valves was determined based on laboratory measurements. It was found that the hydraulic loss due to friction in the lay-flat laterals can be accurately estimated with standard friction loss equations using a smaller effective diameter based on the wall thickness and inlet pressure head. The equivalent length barb loss, expressed as an equivalent length of lateral, was calculated for button emitters, as well as for micro-tubes inserted to lengths of 5 and 10 cm. It was concluded that the barb loss is essentially constant over the micro-tube insertion range of 5-10 cm. The head-discharge relationship and coefficient of manufacturer's variation of pre-punched lateral holes (without emitters), button emitters, and micro-tubes were characterized.

Finally, several IDEal drip irrigation systems in the Central Rift Valley of Ethiopia were evaluated in the field. Recommendations were given for future research

and improvements in the manufacturing, installation, operation, and maintenance of IDEal drip irrigation equipment.

(169 pages)

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NOTATION

The following symbols are used:

A = cross-sectional area
c = length of segment
CvU = coefficient of variation uniformity
D = diameter
D_r = ratio of small to large inside diameters
D_x = measured horizontal diameter
D_y = measured vertical diameter
f = friction factor
f_e = emitter connection loss expressed as an equivalent length of lateral
g = acceleration due to gravity
h = emitter pressure head, height of segment
h_i = emitter pressure head at position, i, along the lateral
h_a = average emitter pressure head
h_f = friction loss
h_{fe} = head loss due to emitter barbs
h_x = pressure in the lateral at a distance, x, from the inlet
h_{ml} = minor losses
H = pressure head
H_{in} = inlet pressure head
J = friction loss gradient
k_{ext} = exit loss coefficient
k_d = emitter discharge coefficient
k_v = valve loss coefficient
K = area of circular segment
K_r = resistance coefficient
L = length
L_e = total equivalent barb length
N_e = number of emitters
P = perimeter
q = emitter flow rate
q_a = average emitter flow rate
Q = flow rate
Q_s = system flow rate
r = correlation coefficient
R = radius
R_e = Reynolds number
R_h = hydraulic radius
R^2 = coefficient of determination
s = arc length
sd = standard deviation

S_e = emitter spacing
t_w = wall thickness
T = temperature
V = velocity
x = emitter discharge exponent
θ = interior angle circular segment
v = kinematic viscosity, coefficient of variation
v_m = coefficient of manufacturer's variation

CHAPTER I

INTRODUCTION

Scarce water resources and/or a lack of water resource technologies are common challenges faced by a large majority of small farmers in developing countries. Affordable irrigation technologies must be developed to help small farmers escape poverty by generating income through increased agricultural productivity. International Development Enterprises (IDE) is a non-profit organization that develops low-cost irrigation technologies which allow farmers to make better use of their water resources and improve their livelihoods.

One technology that has been developed by IDE is the IDEal drip irrigation system. This system consists of very thin-walled (125-500 µm) lay-flat laterals (also called drip tape) that operate at extremely low pressures (less than 2 m of hydraulic head). The laterals are connected to the manifold, or submain, by an inexpensive valve and gasket. The system uses a variety of emitter types, including pre-punched holes in the lateral wall, button emitters, and micro-tube emitters. Up until now, few studies have been done on the hydraulics of the system components. As a result, designers have lacked the information necessary to create effective low-cost irrigation systems.

The objective of this study was to analyze the hydraulics of the individual components of IDEal drip irrigation systems. This was accomplished by completing the following tasks under controlled conditions at the Utah Water Research Laboratory (UWRL) in Logan, Utah:

- Determine the loss coefficient of connector valves;

- Characterize the friction losses in 16-mm diameter laterals with 125-, 200-, 250-, and 500-µm nominal wall thicknesses;
- Determine the emitter connection friction loss as an equivalent length of the lateral (emitter barb loss) for button emitters, and for micro-tube emitters inserted to lengths of 5 and 10 cm;
- Determine the head-discharge relationship and coefficient of manufacturing variation for pre-punched lateral holes, micro-tube emitters, and button emitters; and,
- Determine the coefficient of variation uniformities for the tested system configurations.

Upon completion of laboratory testing, a selection of systems in the Central Rift Valley of Ethiopia was evaluated under actual field conditions. The results are included in Appendices G-L. Evaluations of installation methods, operation and maintenance practices, and overall system performance were performed.

CHAPTER II

LITERATURE REVIEW

There have been many studies on the hydraulics of drip irrigation systems. These studies have commented on the methods and parameters used for micro-irrigation system design. Yildirim and Agiralioglu (2004) compared several of these methods and showed that emitter characteristics are important for design. Provenzano et al. (2005) provided a procedure for evaluating total hydraulic head losses, including an extended local loss evaluation procedure, and a simplified procedure based on the assumption of constant outlet discharge. The results showed a 2.4% error when compared with total head loss measurements on 15 commercially available drip irrigation laterals. Gyasi-Agyei (2007) outlined the uncertainties in drip irrigation lateral parameters and showed that the supplied manufacturing values may be different than the effective field values due to manufacturing variations and other factors.

One difficulty in drip irrigation lateral hydraulics is in determining a correct estimation of the friction factor, f, as used in the Darcy-Weisbach equation to determine hydraulic head loss in the lateral. This difficulty arises because of the variation of f along the lateral due to changes in discharge with respect to location. Vallesquino and Luque-Escamilla (2002) accounted for this problem by creating an equivalent friction factor for the length of the lateral. However, it is unknown how this method would apply to a non-circular pipe cross-section due to flexible pipe walls and a low inlet pressure head. Other authors have shown the successful use of the Blasius equation to determine the friction factor for small-diameter drip irrigation laterals (Provenzano and Pumo 2004; Juana et al. 2002a):

$$f = 0.32 R_e^{-0.25} \tag{1}$$

where R_e is the Reynolds Number. The Reynolds number is defined as:

$$R_e = \frac{VD}{v} \tag{2}$$

where V is the velocity in the pipe (m/s); D is the diameter of the pipe (m); and, v is the kinematic viscosity (m^2/s). The kinematic viscosity is a function of temperature and can be approximated by:

$$v = \left(83.9192T^2 + 20{,}707.5T + 551{,}173\right)^{-1} \tag{3}$$

for v in m^2/s; and, temperature, T, in degrees Celsius (Merkley and Allen 2007).

Equation (1) is considered valid for Reynolds numbers between 2,000 and 100,000 in circular pipes flowing full. In cases where the Reynolds number is less than 2,000 (i.e. laminar flow) the following equation can be used (Finnemore and Franzini 2002):

$$f = \frac{64}{R_e} \tag{4}$$

In traditional drip irrigation lateral design, the head loss gradient for the lateral is found using Eq. (5), as described by Watters and Keller (1978), which combines the Reynolds number, Darcy-Weisbach, and Blasius equations to obtain:

$$J = K\frac{Q^{1.75}}{D^{4.75}} \tag{5}$$

where J is the head loss gradient in m/100m; K is a conversion constant that can be adjusted to average conditions; Q is the flow rate in lps; and, D is the inside diameter (ID) of the pipe in mm. The friction loss, h_f, can then be calculated as:

$$h_f = \frac{JL}{100} \tag{6}$$

For non-circular cross-sections, it is generally accepted to use an equivalent diameter, calculated from Eq. (7) for full pipe flow:

$$D = 4R_h \tag{7}$$

where R_h is the hydraulic radius (m):

$$R_h = \frac{A}{P} \tag{8}$$

in which A is the cross-sectional area (m^2); and, P is the perimeter of the cross-section (m). Equation (7) gives reasonably accurate results for turbulent flow, but the results are poor for laminar flow (Finnemore and Franzini 2002).

It is well documented that local losses caused by the emitter connections on a lateral can have a significant impact on the overall hydraulic design of the system (Provenzano and Pumo 2004; Juana et al. 2002a, b). Yildirim (2007) proposed a simple method for the hydraulic design of trickle laterals and showed that in some cases when the local hydraulic losses were ignored, the system designs had significant error. Bagarello et al. (1997) proposed a procedure for evaluating local losses caused by the emitter barb (for those emitters that have barbs) by characterizing pipe-emitter system with an obstruction index. They showed that the loss depends not only on the emitter geometry, but also on the emitter connection and deformation of the pipe around the stem.

There has been much discussion on which method of evaluating drip irrigation system performance is the most appropriate or correct. However, the conclusion can be reached that any uniformity expression can be used because they are all highly correlated (Barragan et al. 2006). Keller and Keller (2003) proposed the use of the coefficient of variation uniformity, *CvU*, as defined in Eq. (9):

$$CvU = 100(1 - v) \tag{9}$$

where v is the coefficient of variation along the lateral, and is defined as:

$$v = \frac{sd}{q_a} \tag{10}$$

where sd is the standard deviation of all emitter flows (lph); and, q_a is the average emitter discharge (lph). Wu and Barragan (2000) also proposed using a *CvU* equivalent. The performance criteria of *CvU* for low-cost drip irrigation systems serving small plots is: above 88% is excellent; from 88% to 80% is good; from 80% to 68% is acceptable; and less than 68% is unacceptable (Keller and Keller 2003).

There are many hydraulic factors that influence drip irrigation system performance and water application uniformity. Wu (1997) showed that the emitter spacing and manufacturer's variation have a much greater effect on overall system uniformity than the hydraulic design. Ella et al. (2008) measured the uniformity of IDEal low-cost drip systems at heads of one to three meters. They showed that the emitter discharge uniformity increased with increasing head. Bhatnagar and Srivastava (2003) reported emission uniformities of 90% in gravity-fed drip irrigation systems. Thus, in order to properly design a drip irrigation system, the hydraulic characteristics of the components must be known.

CHAPTER III

EXPERIMENTAL DESIGN

The components of the IDEal drip irrigation system were tested under controlled conditions in a greenhouse at the Utah Water Research Laboratory. Experiments were designed to allow independent measurement and subsequent hydraulic analysis of selected components of the system. An apparatus was built to allow testing of the components under a variety of pressures (or hydraulic heads) and flow rates.

The testing apparatus consisted of two constant-head tanks connected by an elevated 18.4-m long "runway" which was placed diagonally across the floor of the greenhouse. The runway, which provided a supportive platform for the lateral, was built in 3-m sections using wooden 2 x 4s, 2 x 6s, and wire mesh (see Fig. B.1). The concrete floor of the greenhouse is uneven, so each runway section was leveled independently using blocks and shims (Fig. 1). After completing the leveling work, the difference between the maximum and minimum elevations along the entire length of the runway was 4 mm.

The runway was constructed with two levels. As seen in Fig. 1, the upper level was constructed of metal hardware cloth to support the IDEal lateral. The lower level was a wooden plank that served as a shelf to place containers for measuring individual emitter flow rates. In this manner, the emitters could discharge through the hardware cloth and into the measuring cups, allowing for convenient evaluation of average emitter flow rates.

Fig. 1. Testing runway. The runway included wire mesh to support the lateral and a shelf for the catch cups (two of which are shown here).

The two constant-head tanks were constructed of 8-inch nominal diameter PIP-PVC pipe and were 3 m tall. The upstream and downstream pipes were capped on the bottom and stood up vertically in each corner, serving as reservoirs, and were secured to the structural steel frame of the greenhouse. The upstream (supply tank) was fed by a common garden hose connected to the potable water supply. One-inch holes were drilled into the sides of each tank at 10-cm intervals, forming overflow holes. In the upstream tank, the holes were plugged using rubber stoppers. The stopper at the desired head on the tank was removed, allowing excess water to overflow, thus maintaining a constant head under steady-state conditions. The tank at the downstream end of the lateral operated in a similar manner, but the overflow holes were threaded so that a hose could be connected to a spout inserted into the overflow hole, facilitating measurement of the flow rate, as seen in Fig. 2. The tanks were sealed to eliminate leakage. Both tanks were

Fig. 2. Downstream tank. The overflow holes were tapped to facilitate flow measurement.

fitted with piezometers for measurement of the hydraulic head (see Fig. B.2), and the maximum hydraulic head obtainable at each tank was 2.2 m.

Flow measurement was done using the volumetric method (i.e. measuring the time required to fill a container to a specific volume, as shown in Fig. B.3), under steady state conditions, as stated previously. The volume was measured using a 4-L beaker with 250-ml graduations. The beaker was calibrated, and a correction term of 100 ml was subtracted from each graduation. The flow rate was measured three times and averaged for each run of each test.

The plastic lateral pipe to be tested was connected to the upstream tank using the IDEal grommet and connector valve (see Fig. B.4). The downstream lateral-tank connection was a small section of half-inch aluminum tubing, to which the lateral pipe could slide over and be fastened. The difference between the elevations of the tank-lateral connections (lateral inlet and outlet) was 2.4 mm. Thus, the slope of the lateral was essentially zero.

Head Loss in Connector Valves

The valve head loss was calculated by using two different configurations. In the first configuration, the valve was connected to the supply tank and a small piece of lateral was connected to the valve. The test was run at different pressure heads and the flow, Q, was calculated by the volumetric method. The valve loss coefficient, k_v, was then calculated for this free discharge condition by rearranging Eq. (11) to obtain Eq.(12):

$$H_1 = \frac{Q^2}{2gA^2} + k_v \frac{Q^2}{2gA^2} \tag{11}$$

$$k_v = H_1 \frac{2gA^2}{Q^2} - 1 \tag{12}$$

where H_1 is the upstream head elevation (m); g is the acceleration due to gravity (9.81 m/s^2); and, A is the cross-sectional area of the valve outlet (m^2). The valve loss coefficient takes into account both the entrance losses from the upstream tank and the losses through the valve. An exit loss of one velocity head (based on valve outlet inside diameter) was assumed, and this is consistent with standard practices.

During testing, it was noticed that the distance of the discharge jet through the valve would suddenly decrease at one point as the head increased. It was determined that at low flows the valve was not flowing full but when the pressure head was sufficient, the valve would flow full. Thus, another testing configuration was created to account for this problem, and the data points for non-full conditions were discarded. At high heads, corresponding to relatively high flows, the valve flowed full, even though it was discharging into the open air.

For the testing configuration at low heads the small piece of lateral was removed and the valve outlet was connected to a small downstream tank, as shown in Fig. 3. The water in the downstream tank created a back-pressure on the valve, forcing it to always flow full, even at low heads. The downstream tank was fitted with a spout so that the overflow would spill free of the tank wall (see Fig. B.5). The test was performed at various heads and the volumetric method was again used to determine the average flow rate. The presence of the downstream tank requires the addition of another term, the downstream tank elevation, H_3, to Eq. (11). Thus, applying the Bernoulli theorem to Fig. 3:

$$H_1 = H_3 + k_v \frac{Q^2}{2gA_2^{\;2}} + \frac{Q^2}{2gA_2^{\;2}} \tag{13}$$

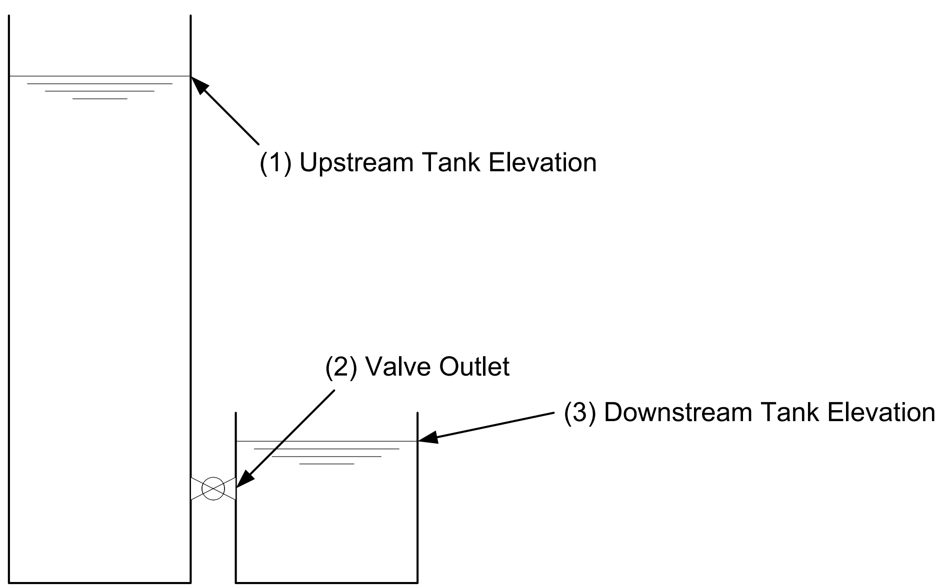

Fig. 3. Valve test configuration #2

Solving for the valve loss coefficient:

$$k_v = \frac{H_1 - H_3 - \dfrac{Q^2}{2gA_2^{\ 2}}}{\dfrac{Q^2}{2gA_2^{\ 2}}} = \frac{H_1 - H_3}{\dfrac{Q^2}{2gA_2^{\ 2}}} - 1 \tag{14}$$

where H_1 is the upstream tank elevation (m); H_3 is the downstream tank elevation (m); Q is the measured flow rate (m^3/s); and, A_2 is the cross-sectional area of the valve outlet (m^2). Equation (11) is simply a special case of Eq. (13), where H_3 is taken to be zero.

Six valves were selected at random and tested. In the first five valves the manufacturing debris was removed from the stopcock and valve chamber prior to testing. In the sixth valve, testing was done before and after the removal of the manufacturing debris. Testing was also done on valve number one under both hot (35°C air temperature) and normal conditions (20-30°C). In addition, the valve was tested with the stopcock rotated 180 degrees.

Head Loss Due to Friction in the Laterals

The friction (hydraulic) loss in IDEal laterals with wall thicknesses of 125, 200, 250, and 500 µm was calculated based on experimental measurements. The lateral (without emitters) was connected to the head tanks as diagrammed in Fig. 4. The valve used to connect the lateral to the upstream tank was the first valve tested in the valve loss tests. The average flow rate was calculated from the overflow at the downstream tank using the volumetric method. The test was performed for a range of pressures by: (1) maintaining a constant water level in the downstream tank and incrementally increasing the water level in the upstream tank; (2) maintaining the water level in the upstream tank

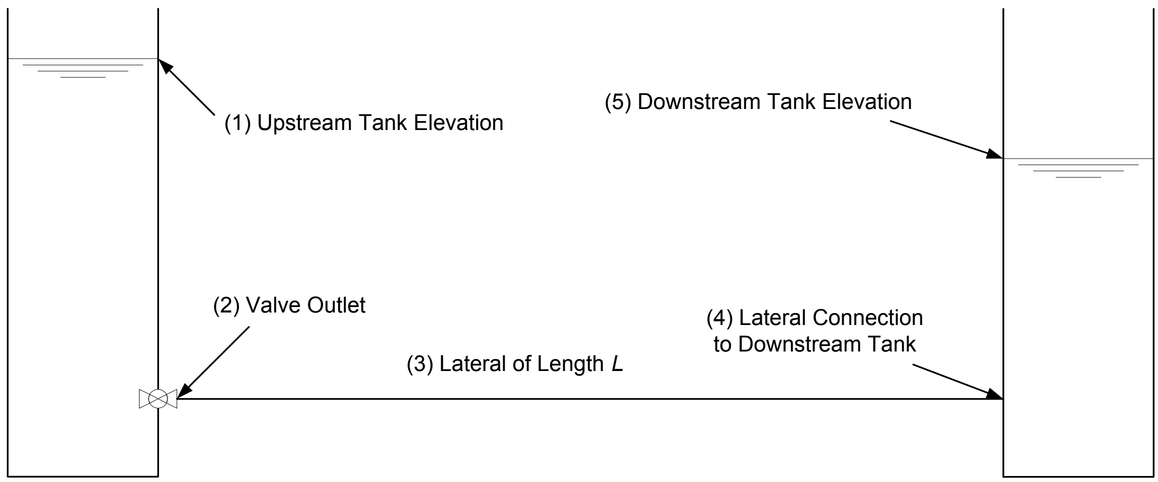

Fig. 4. Friction loss test setup

at the maximum value (corresponding to the highest spill port), and incrementally increasing the water level in the downstream tank; and, (3) fixing the head differential across the lateral, and raising the upstream and downstream tank water levels simultaneously. The first of these three procedures was used to obtain the majority of the data points, while the latter two were used occasionally to verify that the results were independent of the testing procedure.

The water temperature was measured periodically throughout each test at the lateral inlet and outlet. Also, the time and ambient air temperature were recorded at the beginning of each test run.

The diameter of the lateral was measured at the center point of the lateral in both the horizontal (D_x) and vertical (D_y) directions using a caliper (see Fig. B.6). Using these two measurements, the hydraulic radius of the lateral cross section was estimated by calculating the area and perimeter of a circular segment, as shown in Fig. 5. In this figure, h and c were calculated using Eqs. (15) and (16), respectively:

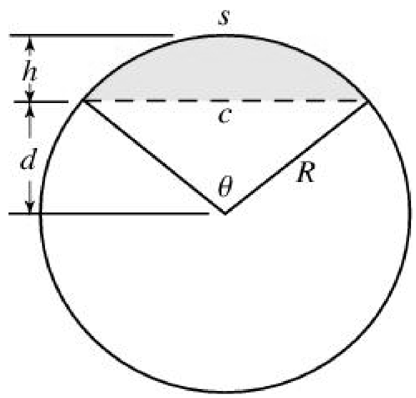

Fig. 5. Circular segment geometry

$$h = \frac{D_y - 2t_w}{2} \tag{15}$$

$$c = D_x - 2t_w \tag{16}$$

where D_y is the measured diameter in the vertical direction; t_w is the lateral wall thickness; and, D_x is the measured diameter in the horizontal direction. With h and c calculated, the area and perimeter of the segment were determined by first calculating the remaining variables in Fig. 5 from Eqs. (17)-(20):

$$R = \frac{c^2}{8h} + \frac{h}{2} \tag{17}$$

$$\theta = 2\sin^{-1}\frac{c}{2R} \tag{18}$$

$$s = R\theta \tag{19}$$

$$K = \frac{R^2}{2}\left(\theta - 2\sin\theta\right) \tag{20}$$

where K is the area of the segment (m^2); and, all other variables are as previously defined, and as illustrated in Fig. 5. Thus, the area, A, and perimeter, P, of the lateral cross-section were calculated as:

$$A = 2K \tag{21}$$

and,

$$P = 2s \tag{22}$$

Using Eqs. (21) and (22), the hydraulic radius was calculated from Eq. (8). As mentioned earlier, for non-circular cross-sections it is generally accepted to use Eq. (7) to obtain an equivalent diameter of the lateral. Alternatively, the equivalent diameter was taken simply as the height of the lateral, which represents the maximum diameter of a round pipe that could fit inside the lateral at a given pressure. This was found by taking the measured diameter in the vertical direction, D_y, minus twice the wall thickness. In theory, the cross-sectional area near the creases (formed along the sides of the lateral when it is rolled up in the factory) does not contribute to the flow path diameter. In all subsequent lateral pipe flow calculations it was assumed that the equivalent diameter of the lateral was constant along the length.

With the above measurements and calculations completed, the Bernoulli theorem was applied to Fig. 4 to obtain Eq. (23):

$$H_1 = H_5 + h_f + h_{ml} \tag{23}$$

where h_f is the friction loss as calculated from Eq. (24), the Darcy-Weisbach equation; and, h_{ml} accounts for the local losses in the valve, at the valve-lateral connection, and at the lateral-downstream tank connection, as shown in Eq. (25):

$$h_f = f \frac{L}{D_3} \frac{V_3^2}{2g} \tag{24}$$

$$h_{ml} = k_v \frac{V_2^2}{2g} + K_r \frac{V_2^2}{2g} + k_{ext} \frac{V_4^2}{2g} \tag{25}$$

In the above equations, f is the friction factor; k_v is the valve loss coefficient as calculated from the results of the previous section; k_{ext} is the exit loss coefficient (assumed to be equal to one); and, K_r is the resistance coefficient of the sudden enlargement (expansion) at the valve-lateral connection. The value of K_r is calculated from Eq. (26) (King and Brater 1963):

$$K_r = \left(1 - D_r^{\,2}\right)^2 \tag{26}$$

where D_r is the ratio of the small to large inside diameters, which in this case pertains to the valve outlet inside and outside diameters, respectively.

Upon obtaining the friction and minor losses, Eqs. (23) and (24) can be combined and solved for the friction factor, f:

$$f = \frac{H_1 - H_5 - h_{ml}}{\frac{L}{D_3}\frac{V_3^2}{2g}} \tag{27}$$

For each lateral wall thickness, the measured (actual) results of the friction loss in the lateral were compared to the results of four different methods of estimation. In all methods the Darcy-Weisbach equation, Eq. (24), was used to calculate the friction loss. The methods differed based on the values used for friction factor, f, and equivalent diameter of the lateral. The results of the four methods were analyzed to determine an effective method of accurately estimating the friction loss in lay-flat laterals. The most effective method for estimating the friction loss in practical application is not necessarily the method that represents the "best-fit" of the experimental data. However, the "best-fit" method was used for subsequent experimental calculations. A summary of the methods is found in Table 1.

Table 1. Methods of Estimating Friction Loss

	Estimation Method			
Parameter	1	2	3	4
f	Eqs. (1), (4)	Empirical	Empirical	Eqs. (1), (4)
D	Measured	Measured	Based on *H*	Based on *H*

Equations (1) and (4) were used to estimate the friction factor in methods one and four. For the second and third methods of friction loss estimation, an exponential equation was fit to the data to define the relationship between friction factor and Reynolds number. The measured values of equivalent diameter were used in methods one and two. Methods three and four used a specified value for the lateral diameter based on the hydraulic head. Each method was completed twice; once for the data based on the equivalent diameter equal to four times the hydraulic radius, and again for the data based on the equivalent diameter equal to the height of the lateral, as described above.

A relationship between the equivalent diameter and pressure was established by calculating the pressure at the point where the diameter measurement was taken, as shown in Eq. (28):

$$h_x = H_1 - k_v \frac{V_2^2}{2g} - K_r \frac{V_2^2}{2g} - \frac{x}{L}\left(H_1 - H_5 - h_{ml}\right) \tag{28}$$

where x is the distance from the lateral inlet to the point of diameter measurement (m); and, h_x is the pressure head at that location (m).

Emitter Barb Loss

The additional friction loss caused by the emitter barb protruding into the lateral was determined by using the same test configuration and procedure as the lateral friction loss tests. Emitters were plugged to prevent any discharge and were inserted into the top of the 250-μm wall thickness pre-punched lateral (see Figs. B.7, B.8). The test was done with the micro-tube emitters inserted to lengths of 5 cm and 10 cm, respectively, as this represents the typical range of insertion in practice (Jack Keller, personal communication, March 2008). The micro-tubes were those with a green stripe, an inside diameter of 1.5-1.8 mm, and an outside diameter of 3 mm. The test was also performed with the button emitters inserted into the pre-punched lateral. The lateral-emitter connection is shown in Fig. 6. It was assumed that the emitter barb loss of the pre-punched holes is negligible.

The additional friction loss caused by the emitter barbs, h_{fe}, was found by adding this term to Eq. (23), which follows the configuration of Fig. 4, to obtain Eq. (29):

$$H_1 = H_5 + h_f + h_{ml} + h_{fe} \tag{29}$$

Rearranging Eq. (29),

$$h_{fe} = H_1 - H_5 - h_f - h_{ml} \tag{30}$$

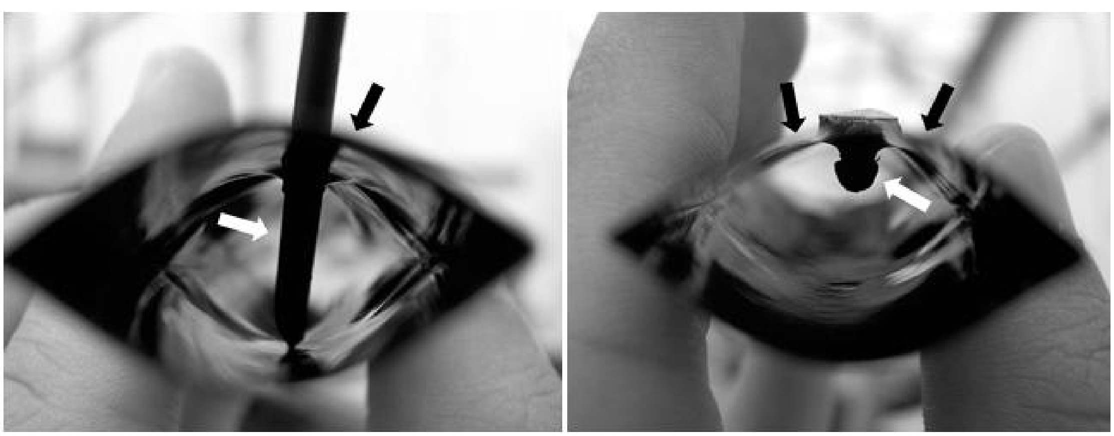

Fig. 6. Emitter barbs. End view of the plastic lateral hose in which the micro-tube emitter barb (5-cm insertion) is shown on the left, and the button emitter barb is seen on the right. White arrows indicate the emitter barb on the inside of the lateral, while black arrows indicate the lateral wall.

The emitter connection friction loss as an equivalent length of the lateral, f_e, is found by first obtaining the total equivalent length, L_e, using the Darcy-Weisbach equation:

$$h_{fe} = f \frac{L_e}{D_3} \frac{V_3^2}{2g} \quad (31)$$

And rearranging to obtain,

$$L_e = \frac{h_{fe}}{f} \frac{2g}{V_3^2} D_3 \quad (32)$$

Finally,

$$f_e = \frac{L_e}{N_e} \quad (33)$$

where N_e is the number of emitters along the length of the lateral.

Emitter Performance

The emitter performance tests determined the head-discharge relationship and the coefficient of manufacturer's variation, ν_m, for each type of emitter. The tests also determined the coefficient of variation uniformity, *CvU*, along the lateral at various pressures. The pre-punched lateral, with emitters inserted and unplugged, was attached to the upstream tank in the same manner as described above for the previous tests. The downstream end of the lateral was not attached to the downstream tank, but was plugged by creating a kink in the line (see Fig. B.9). The tests were completed with the emitters on the bottom side of the lateral, allowing the emitters to discharge directly through the wire mesh (see Figs. B.10 and B.11). As in the other tests, the lateral was tested under a range of pressures. The flow rates from the individual emitters, q_i, were measured volumetrically (three times and averaged) by placing catch cups under each emitter.

By combining the information from the previous tests, the head at the first emitter, h_1, and each subsequent emitter, h_i, was calculated from Eqs. (34) and (35) , respectively, following a modified Fig. 4 (omitting positions 4 and 5):

$$h_1 = H_1 - k_v \frac{V_2^2}{2g} - K_r \frac{V_2^2}{2g} - h_{f_1} - h_{fe_i} \tag{34}$$

$$h_i = h_{i-1} - h_{f_i} - h_{fe_i} \tag{35}$$

where h_f is from Eq. (24), but with the emitter spacing, S_e, substituted for the lateral length, L, at each emitter. Similarly, h_{fe} is from Eq. (31) with the equivalent length barb loss, f_e, substituted for L_e at each emitter. In this case, both h_f and h_{fe} are based on the diameter of the lateral as obtained from the methods described previously in the "Head Loss Due to Friction in the Laterals" section of this chapter. The equivalent length barb loss was estimated at each emitter along the lateral based on the results of the previous section, and dependent on the Reynolds number. The flow rate, Q_i, used to calculate the friction loss and the emitter barb loss for each emitter was calculated from Eq. (36):

$$Q_i = Q_{i-1} - q_{i-1} \tag{36}$$

The flow in the lateral prior to the first emitter is the sum of all emitter flow rates:

$$Q_1 = Q_s = \sum_{i=1}^{n} q_i \tag{37}$$

For each run and corresponding pressure, the discharge coefficient of variation uniformity was found from Eq. (9).

The completion of all runs yielded a set of head and discharge data for each emitter on the lateral, from which the overall head-discharge relationship was obtained. This relationship is described by Eq. (38):

$$q = k_d h^x \tag{38}$$

where q is the emitter flow rate (lph); and, h is the hydraulic head (m). The discharge coefficients, k_d and x, were determined by linear regression for each emitter tested. The average k_d and x were then calculated to obtain the overall head-discharge relationship for each emitter type.

With the head-discharge relationship for each emitter known, the average flow for all emitters at one meter of head was calculated. The corresponding manufacturer's coefficient of variation, v_m, can then be calculated as:

$$v_m = \frac{sd}{q_a} \tag{39}$$

where q_a is the average emitter flow (lph) at 1 m of head; and, sd is the standard deviation of all emitter flows (lph).

Additional Testing

Observations made during testing revealed that additional information about the system, but not necessarily about hydraulics, were of value. As a result, some additional tests and measurements were carried out to address these observations. These tests concerned: lateral wall thickness (Appendix D), emitter spacing (Appendix E), and the effect of time-lag on emission uniformity (Appendix F).

Upon completion of laboratory testing, a selection of IDEal drip irrigation systems in the Central Rift Valley of Ethiopia was evaluated under actual field conditions. The results are presented in Appendices G-L. Evaluations obtained information regarding installation methods, water supply, operation and maintenance practices, system layout, and emission uniformity. The experimental design and results for these tests are found in the respective appendices; however, the implications of the results are included in the "Recommendations" section of the chapter on Summary, Conclusions, and Recommendations.

CHAPTER IV

RESULTS AND DISCUSSION

Head Loss in Connector Valves

A summary of loss coefficient values, k_v, for six randomly selected connector valves is presented in Table 2. Each of the valves was prepared by carefully removing the excess plastic material (debris) which was produced from the extrusion process at the factory. Valve testing was done at normal air temperature conditions (20-30°C) in the UWRL greenhouse. The average coefficient of variation of measured flows for all tests was 0.77%. The overall maximum k_v was 9.81 and the minimum was 4.70, which yields a maximum difference of 5.11. The overall average k_v was calculated from the average k_v of each valve. The overall average was 7.27, with a standard deviation of 1.50, and a coefficient of variation of 21%. The values of k_v for each valve are shown in Fig. C.1.

The head-discharge relationship for each valve tested is shown in Fig. 7. Table A.1 shows flow rates at various pressure heads for each valve; the flow rate was

Table 2. Valve Loss Coefficients for Six Connector Valves

Valve	k_v					
No.#	Max	Min	Difference	sd	Average	ν
1	9.81	8.45	1.36	0.34	9.08	4%
2	7.16	6.63	0.54	0.14	6.92	2%
3	5.39	4.70	0.69	0.18	5.00	4%
4	8.99	8.16	0.83	0.20	8.72	2%
5	6.87	5.83	1.04	0.26	6.48	4%
6	7.57	7.13	0.44	0.14	7.41	2%
Overall	9.81	4.70	5.11	1.50	7.27	21%

Note: Difference *is the difference between Max and Min*

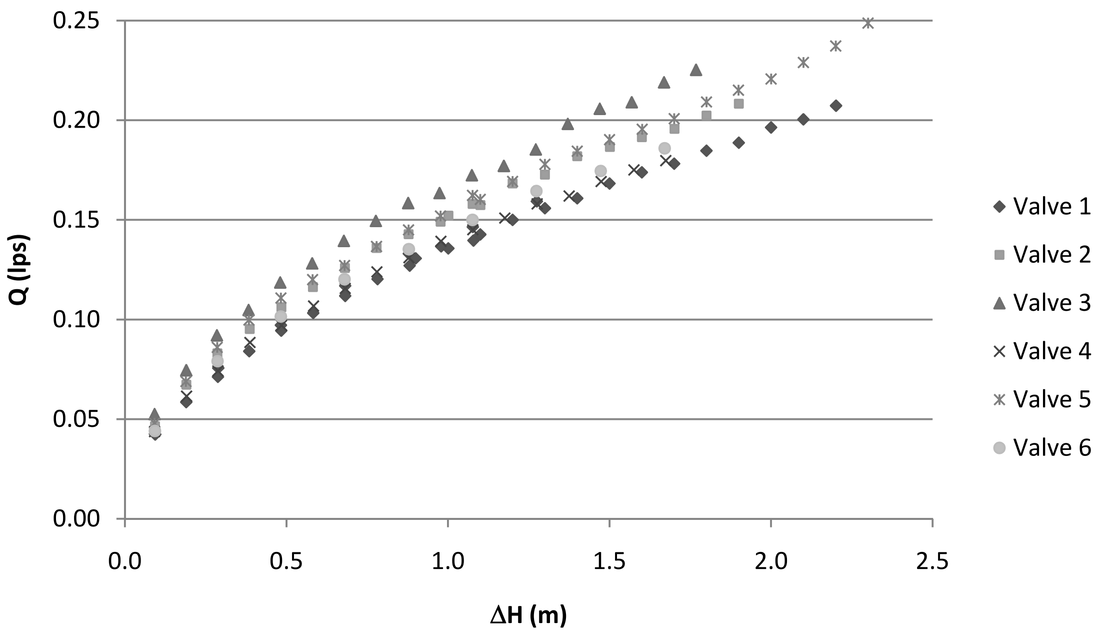

Fig. 7. Measured head-discharge data for six connector valves

estimated from the head-discharge relationship for each valve, which was determined by fitting an exponential equation to each data set as shown in Fig. 7 (average R^2 = 0.9991). As seen in Table A.1, the flow rate varies by 8%, on average, for a given pressure head.

The inside diameters of each valve are shown in Table A.2. Two perpendicular measurements were taken at each location and averaged. The average inlet and outlet inside diameters were 10.2 and 11.1 mm, respectively. The average minimum inside diameter of the entrance and exit holes through the stopcock was 7.4 mm. The diameter of the hole in either side of the stopcock was not always equal on each side, and in some cases the hole was not circular.

Manufacturing Debris

The connector valves contained significant amounts of debris leftover from the extrusion manufacturing process. As a result, valves 1-5 were cleaned of debris prior to testing. To investigate the effect of the presence of manufacturing debris on valve performance, valve 6 was tested before and after the removal of debris. Valve 6 is shown in Fig. 8 before and after the removal of manufacturing debris. Debris was found in both the valve chamber and the valve stopcock (see Figs. B.12, B.13).

The average valve loss coefficients for the valve before and after debris removal are shown in Table 3. Before debris removal, the average k_v was 10.5, with a coefficient of variation of 4%. After removal of debris, the same valve had an average k_v of 7.41 and a coefficient of variation of 2%. Thus, the removal of debris from the valve decreased the value of the valve loss coefficient by 29% and cut the coefficient of variation in half. Figure C.2 shows the values of k_v for the valve before and after debris removal at various hydraulic heads.

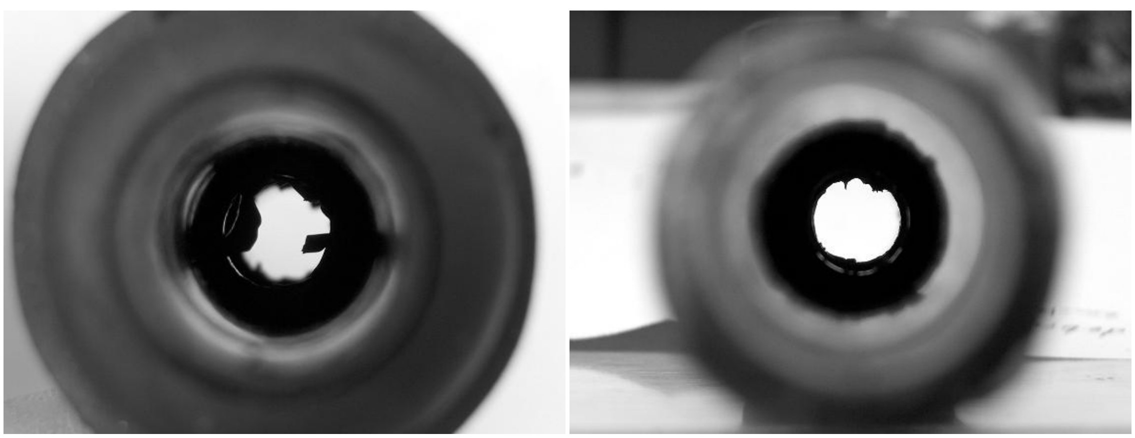

Fig. 8. End view of manufacturing debris in the valve. The valve before removal of the debris is shown on the left, and the same valve after cleaning is shown on the right.

Table 3. Valve Loss Coefficients for Valve 6 Before and After Debris Removal

	k_v		
	Average	sd	ν
With debris	10.5	0.40	4%
Without debris	7.41	0.14	2%

The head-discharge relationship for the valve with and without debris is shown in Fig. 9. This figure illustrates that when debris is removed from the valve a higher flow will result for the same head. Thus, the valve head loss decreases when debris is removed. The amount of flow increase due to manufacturing debris removal is shown in Table A.3. In this table, flow was estimated from the head-discharge relationship by fitting an exponential equation to the data in Fig. 9 (R^2 = 0.9980 and 0.9997 for the valve with and without debris, respectively). On average, the flow increased by 17% with the manufacturing debris removed.

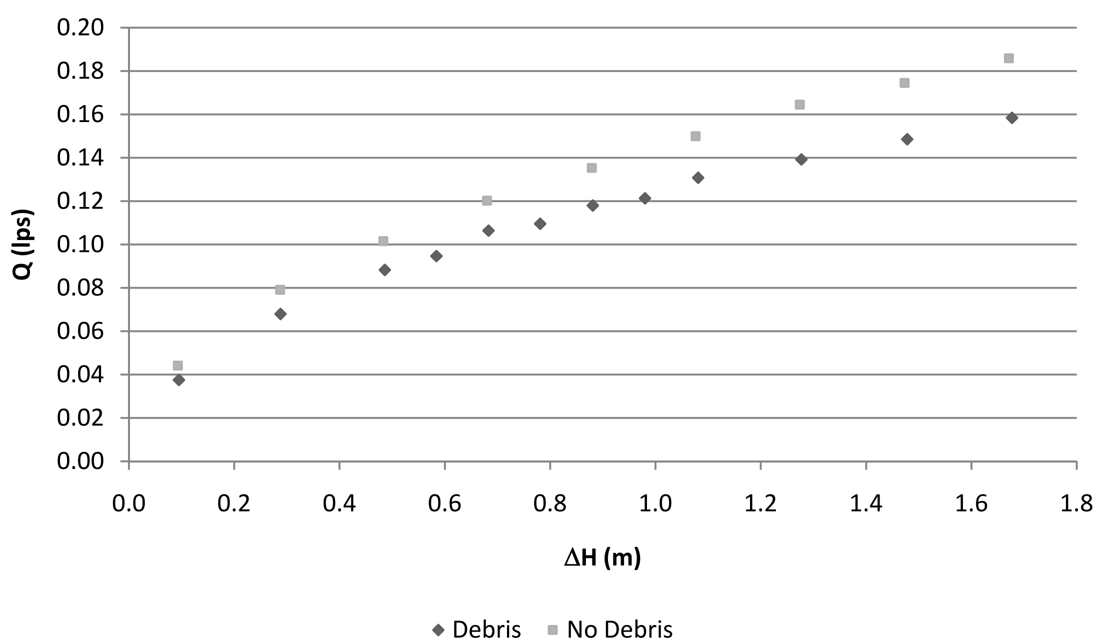

Fig. 9. Effect of manufacturing debris on the valve head-discharge relationship

Temperature Effects

Valve 1 was tested under both “normal” (20-30°C) and relatively hot (35°C) temperature conditions to investigate the effect of air temperature on valve performance.

The results are shown in Fig. C.3. The average valve loss coefficient for valve 1 under hot conditions was 9.17, compared to an average k_v of 9.08 for "normal" conditions. Thus, it can be determined that for this range of conditions, air temperature did not have a significant impact on valve performance. The average temperature of the water supply was approximately 13°C, and it is probable that the flow of cold water through the valve maintains the valve at a colder temperature than the surrounding air. This will not necessarily be the case under actual field conditions.

Stopcock Orientation

The connector valve can be operated by turning the stopcock in either direction. As mentioned above, it was observed that the diameters of the entrance and exit holes in the stopcock are not equal. In addition, the presence of manufacturing debris in the valve is not equally distributed. Thus, tests were performed to see if the orientation of the stopcock would have a significant impact on valve performance (Fig. C.3). The average k_v of valve 1 with the stopcock reversed 180 degrees was 8.48. This amounts to a difference of 0.60 when compared to the k_v measured at the initial fully-open position of the stopcock.

Head Loss Due to Friction in the Laterals

The results of the friction loss tests are reported individually for the various lateral wall thicknesses. Only the results of the first and fourth methods of friction loss estimation (see Table 1) are reported, as these represent the standard and most practical methods, respectively. The fourth estimation method is the most practical because it is not dependent on measured diameters. While the differences between the estimated friction factors of the two methods are relatively small, the fourth estimation method uses a different (usually smaller) effective diameter to accurately estimate the friction loss. The second and third methods were applied in order to obtain the "best-fit" method for subsequent experimental calculations, and the results are reported where relevant.

The measured friction loss is the same regardless of which effective diameter estimation is used ($4R_h$ or lateral height). However, the results of estimated friction loss shown below are based on the use of the lateral height as the equivalent diameter, as opposed to using the calculation of hydraulic radius, as explained in the "Experimental Design" chapter. This is because in all cases, use of the hydraulic radius led to underestimation of the friction loss. In most cases, use of the lateral height in the calculations improved the friction loss estimation. This supports the theory that the lateral cross-section area in the creases does not greatly impact the flow path diameter. The values used for the effective diameter in the friction loss estimation were not arbitrarily chosen, but are based on the laboratory measurements of the diameter-pressure head relationship.

Reynolds numbers for the tests ranged from 1,000 to 10,000, which is in the typical range for trickle irrigation tubing (Watters and Keller 1978). In application, the friction loss at the downstream end of the lateral, where laminar flow occurs when emitters are present, is very low. Therefore, the accuracy of friction loss estimation at these points is less significant. The majority of the friction loss will be at the entrance of the lateral, where higher velocities and turbulent flow occurs. In all cases, the measured and estimated friction factors converged as the flow became more turbulent.

125-μm Wall Thickness

The measured friction factor as a function of the Reynolds number for the lateral with 125-μm wall thickness is shown with the results of estimation methods one and four in Fig. 10. The average coefficient of variation of measured flows was 0.74%. Figure 10 shows the flow becoming laminar below Reynolds numbers of 2,000. The measured and estimated values of friction factor converge as the flow becomes more turbulent.

The effective diameter as a function of pressure head is shown in Fig. 11. The fourth estimation method used an effective diameter of 15.5 mm when the pressure head was less than 0.5 m, and an effective diameter of 16 mm when the pressure head was greater than 0.5 m. The first estimation method accounted for 85% of the measured friction loss on average overall (95% when R_e > 4,000), with a standard deviation of 0.22, a coefficient of variation of 26%, and a correlation coefficient of 0.9923. The fourth

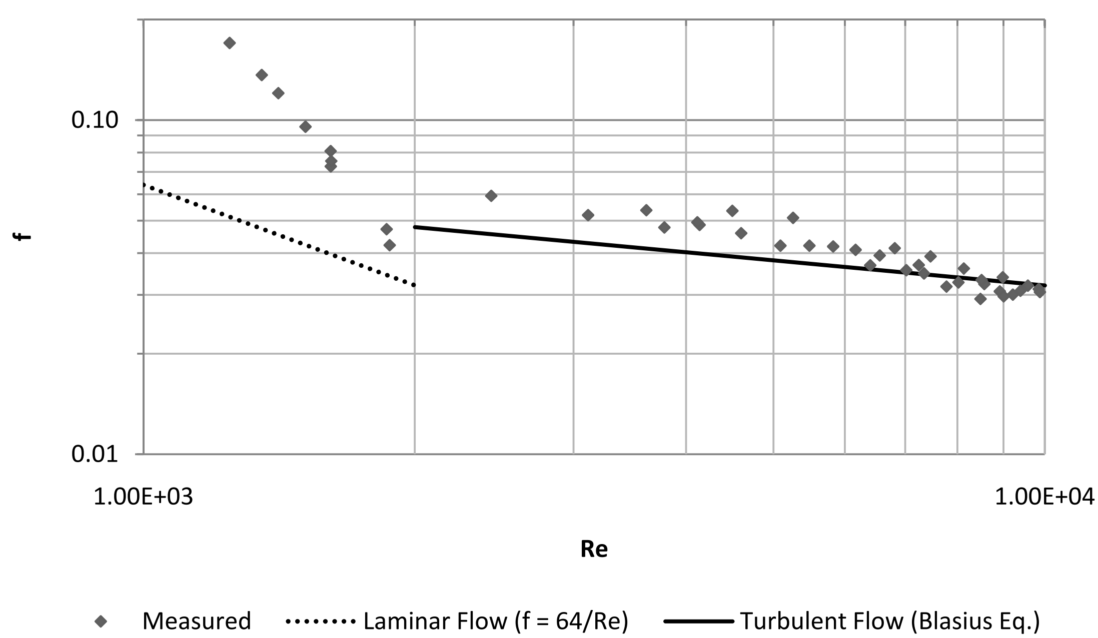

Fig. 10. Friction factor and Reynolds number in the 125-μm wall thickness lateral

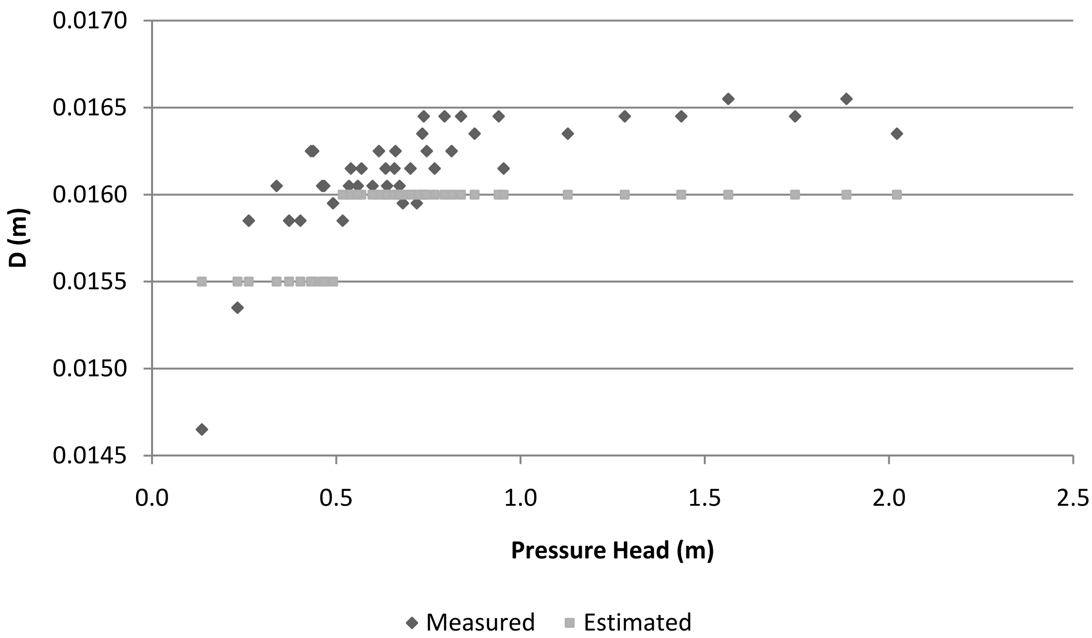

Fig. 11. Effective diameter and pressure head in the 125-μm wall thickness lateral

estimation method accounted for 91% of the measured friction loss on average overall (103% when $R_e > 4{,}000$), with a standard deviation of 0.23, a coefficient of variation of 25%, and a correlation coefficient of 0.9942 (see Fig. C.4). Even at low pressures the lateral inflated to an almost circular cross section; thus, there is little difference between the accuracy of the two estimation methods.

200-μm Wall Thickness

Due to variations observed in the wall thickness of the lateral (see Appendix D), two samples of 200-μm wall thickness lateral were tested to verify the results between samples. The samples came from the same roll, and thus the same manufacturer. The average coefficient of variation of measured flows was 0.57%. The effective diameter as a function of pressure head for the lateral is shown in Fig. 12. Sample two exhibited a

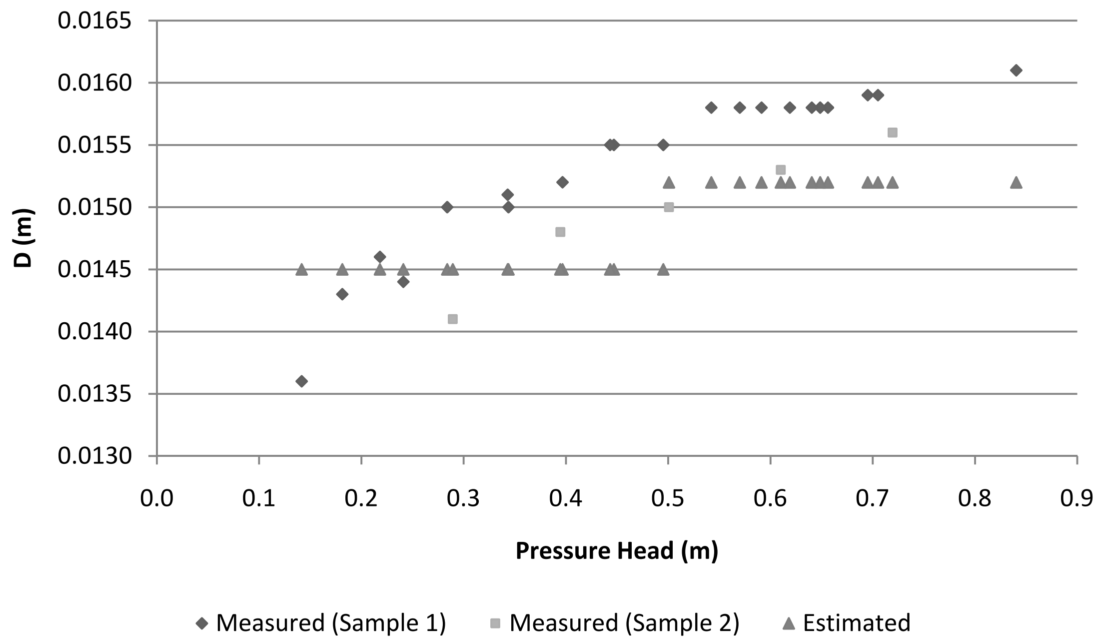

Fig. 12. Effective diameter and pressure head in the 200-μm wall thickness lateral

smaller effective diameter than sample one for the same pressure, suggesting a thicker wall than that of sample one. To account for these variations, the fourth friction loss estimation method used the following criteria: for $H < 0.5$ m, $D = 14.5$ mm; for 0.5 m < $H < 1.0$ m, $D = 15.2$ mm; and, for 2.5 m > $H > 1.0$ m, $D = 15.5$ mm.

The friction factor as a function of the Reynolds number is shown in Fig. 13. The flow became distinctly laminar below Reynolds numbers of 2,000. The measured and estimated values of friction factor converge as the flow becomes more turbulent. The first estimation method accounted for 78% of the measured friction loss on average overall (92% when $R_e > 4{,}000$), with a standard deviation of 0.37, a coefficient of variation of 48%, and a correlation coefficient of 0.9959. The fourth estimation method accounted for 89% of the measured friction loss on average overall (110% when $R_e >$

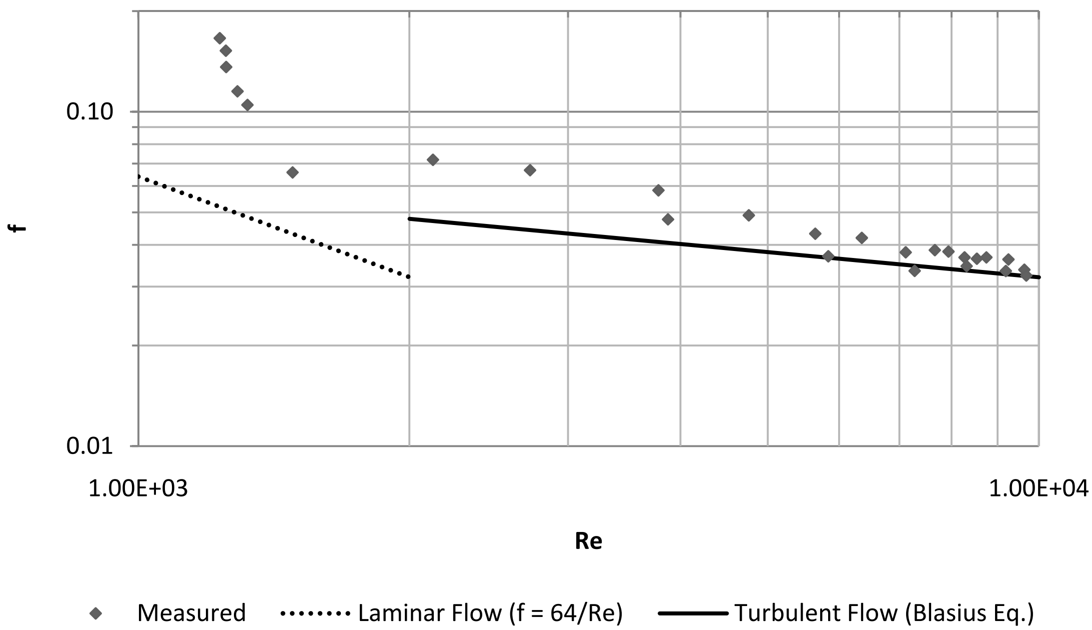

Fig. 13. Friction factor and Reynolds number in the 200-µm wall thickness lateral

4,000), with a standard deviation of 0.29, a coefficient of variation of 32%, and a correlation coefficient of 0.9939 (see Fig. C.5).

250-µm Wall Thickness

Three samples of 250-µm wall thickness lateral, all from the same spool, were tested. The average coefficient of variation of measured flows was 0.60%. The effective diameter as a function of pressure head for the three samples is shown in Fig. 14. Sample one varied significantly from samples two and three, displaying a larger effective diameter for a given pressure. Figure 14 shows the results beginning to converge near a diameter of 16 mm above 0.8 m of pressure. The fourth friction loss estimation method used the following criteria: for $H < 0.5$ m, $D = 13$ mm; for 0.5 m $< H <$ 1.0 m, $D = 15$ mm; and, for 2.5 m $> H >$ 1.0 m, $D = 15.5$ mm.

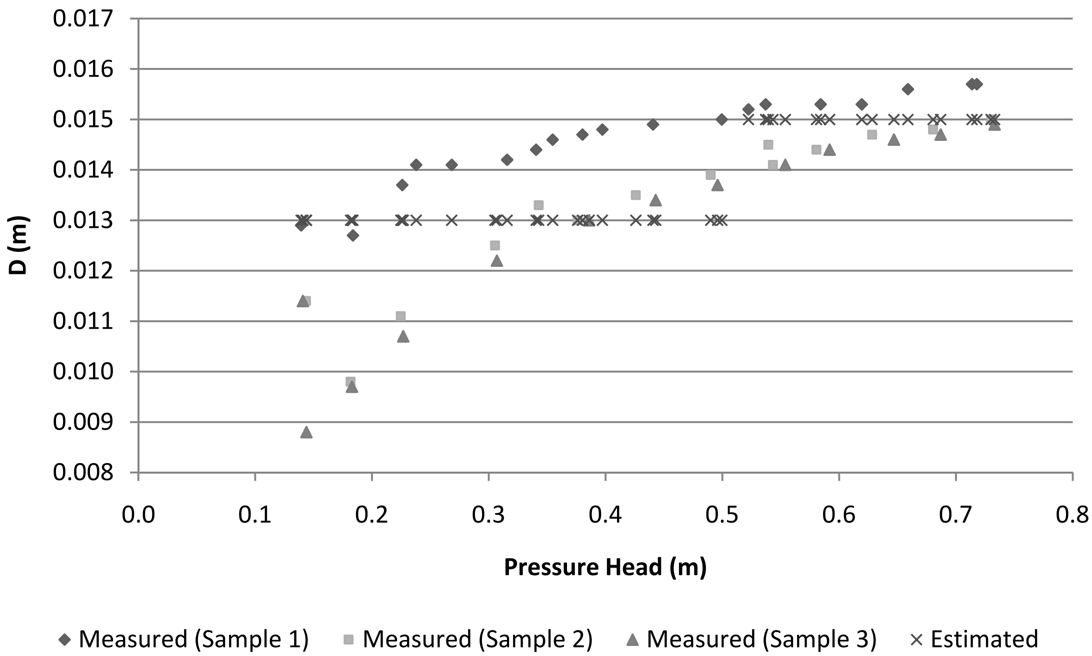

Fig. 14. Effective diameter and pressure head in the 250-μm wall thickness lateral

The friction factor as a function of Reynolds number is shown in Fig. 15. The measured friction factor became unstable below Reynolds numbers of 4,000, which is evidence of a transitional flow regime. Below Reynolds numbers of 2,000, the measured values began to stabilize somewhat, suggesting laminar flow. However, the measured and estimated f values converged as the flow became more turbulent.

The first estimation method accounted for 105% of the measured friction loss on average overall (91% when $R_e > 4{,}000$), with a standard deviation of 0.66, a coefficient of variation of 63%, and a correlation coefficient of 0.9193. The fourth estimation method accounted for 90% of the measured friction loss on average overall (102% when $R_e >$ 4,000), with a standard deviation of 0.21, a coefficient of variation of 23%, and a correlation coefficient of 0.9631 (see Fig. C.6).

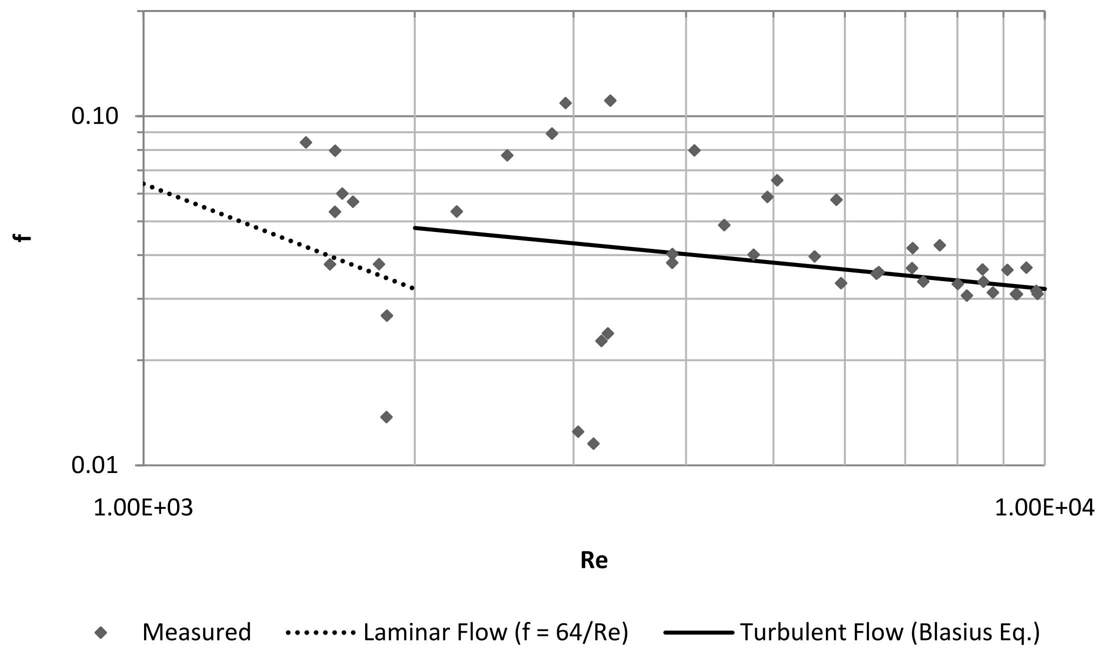

Fig. 15. Friction factor and Reynolds number in the 250-μm wall thickness lateral

The variation in the results between samples gave rise to the concern that the pre-punched lateral of 250-μm wall thickness would differ significantly from the above results. Thus, the friction loss was also measured in the pre-punched lateral. Figure C.7 shows the friction factor at various Reynolds numbers in the pre-punched lateral. Above Reynolds numbers of 4,000, the friction factor remained relatively constant at 0.026, which is considerably less than for the lateral that was not pre-punched. This further suggests a high manufacturing variation. For calculations in subsequent tests which used the 250-μm wall thickness pre-punched lateral, the friction factor was estimated from the following criteria: for $R_e < 2{,}000$, $f = 0.014$; for $2{,}000 < R_e < 4{,}000$, $f = 0.017$; and, for $R_e > 4{,}000$, $f = 0.026$. Using these criteria and the measured values of diameter, 99% of the measured friction loss was accounted for on average overall (100% when $R_e > 4{,}000$), with a standard deviation of 0.12, a coefficient of variation of 12%, and a correlation coefficient of 0.9952.

500-µm Wall Thickness

The results of the friction loss in the lateral of 500-µm wall thickness did not follow the same pattern exhibited in the thinner-walled laterals. Specifically, use of the lateral height as effective diameter in estimation method one drastically overestimated the measured friction loss (230% on average). When using four times the hydraulic radius for the effective diameter, estimation method one only slightly underestimated (86%) the measured friction loss.

As discussed above, the method used to estimate the effective diameter ($4R_h$ or lateral height) is irrelevant when estimating the friction loss; the fourth estimation method can still accurately estimate the friction loss by adjusting the value of the effective diameter accordingly. The major difficulty in accurately estimating the friction loss in the 500-µm sample arises from the effects of temperature on the lateral cross section.

The measured head-discharge of the 500-µm wall thickness lateral is shown in Fig. C.8. This figure shows two curves exhibited by the same sample, but taken at different times of the day; one in the morning and one in the afternoon. The lateral shows a higher discharge in the afternoon for a given pressure. Figure 16 shows the measured effective diameter (equal to $4R_h$) of the lateral as a function of pressure recorded in the morning and the afternoon. The lateral exhibited a greater effective diameter in the afternoon for a given pressure. The typical morning ambient air temperature range in the greenhouse was 20-30°C. Afternoon air temperatures often exceeded 35°C.

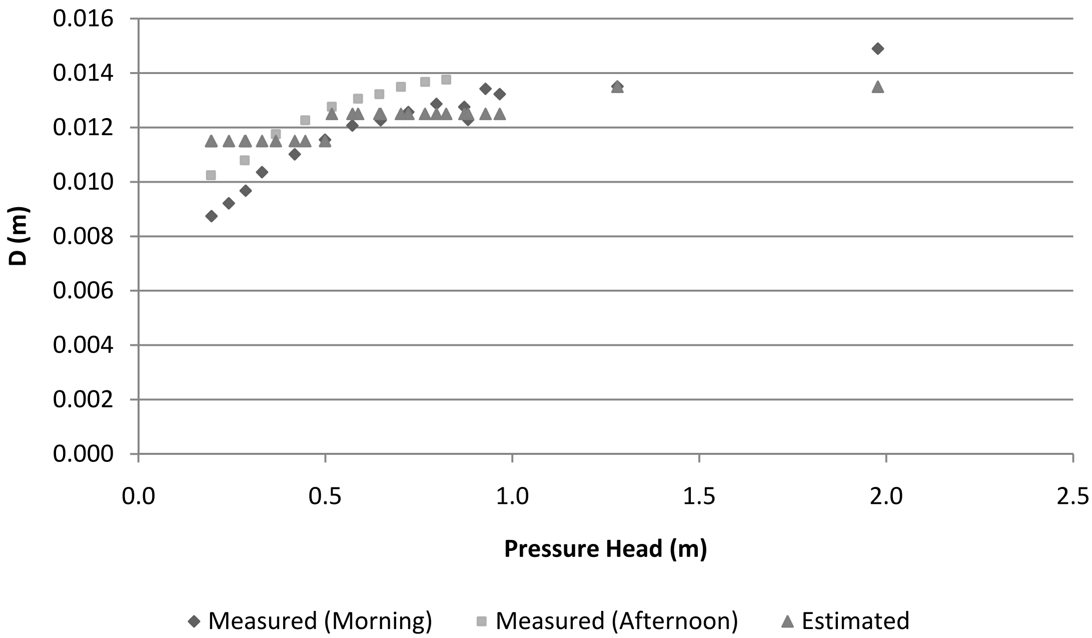

Fig. 16. Effective diameter (equal to $4R_h$) as a function of pressure head in the 500-µm wall thickness lateral

From the above mentioned figures it can be concluded that air temperature has a significant effect on the lateral flow characteristics. After an extended period of time in the sun during testing, the plastic material of the lateral began to soften (it is "thermoplastic" material). This caused the lateral to more fully inflate for a given pressure, increasing the flow. It is also noted that the differences in lateral performance are significant when the water temperature was approximately 13°C, which may be much warmer than actual field conditions. Without the cooling effect of the cold water in the lateral, the plastic would most likely soften even more, further altering the lateral flow characteristics. Furthermore, actual air temperatures in the field could be much greater than the 35°C experienced in "hot" conditions of the laboratory.

The effect of temperature on the lateral was not seen in the laterals of smaller wall thickness for several reasons. The flow of cold water through the thin-walled lateral was enough to overcome the effects of air temperature and direct solar radiation, thus maintaining the lateral at a relatively constant pressure. This was verified by additional testing in the 125-µm sample under hot conditions (35°C). In addition, laterals with thinner walls more fully inflate even at relatively low pressures. The thicker wall requires a larger pressure in order to fully inflate. This was evident in the 500-µm sample, where the measured horizontal diameter, D_x, was on average more than twice the vertical diameter, D_y. However, as the temperature increased, the lateral wall softened, allowing the lateral to more fully inflate, more closely approximating a circular cross section.

The behavior of the effective diameter as a function of pressure is difficult to characterize because of the effects of temperature on lateral wall stiffness. However, the following criteria can be used with relative accuracy to estimate the effective diameter: for $H < 0.5$ m, $D = 11.5$ mm; for 0.5 m $< H <$ 1.0 m, $D = 12.5$ mm; and, for 2.5 m $> H >$ 1.0 m, $D = 13.5$ mm. Using these criteria, the fourth estimation method accounted for 85% of the measured friction loss on average overall (99% when $R_e > 4{,}000$), with a standard deviation of 0.28, a coefficient of variation of 33%, and a correlation coefficient of 0.9402 (see Fig. C.9). The average coefficient of variation of measured flows was 0.40%.

Figure 17 shows the friction factor as a function of the Reynolds number. The measured values became unstable below Reynolds numbers of 3,000, indicating transitional flow. There is no clear distinction of the laminar regime in the measured

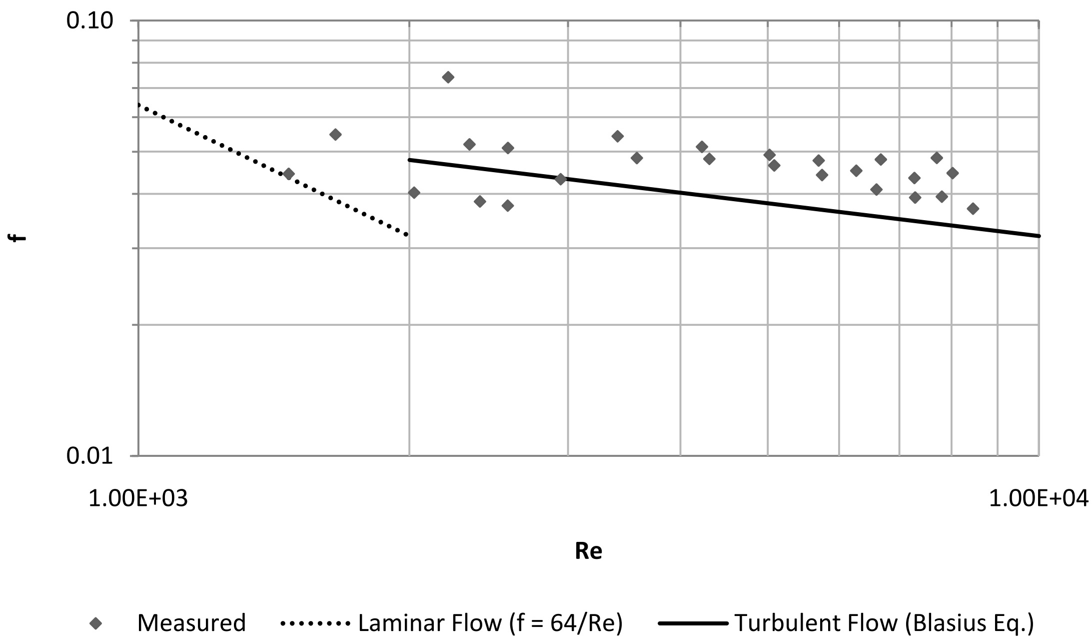

Fig. 17. Friction factor and Reynolds number in the 500-µm wall thickness lateral. In this case $4R_h$, as opposed to lateral height, was used as the effective diameter, measured in both the morning and afternoon.

values; however, the estimated values show the laminar regime at Reynolds numbers less than 2,000.

Emitter Barb Loss

The emitter barb loss tests were run on separate samples of 250-µm wall thickness pre-punched lateral than those used for the friction loss tests. However, the results of the friction loss test, as presented above for the pre-punched lateral, were applied in the calculations to determine the value of f_e for each emitter type: micro-tubes and buttons.

Micro-tube Emitters

The measured data for the emitter connection friction loss as an equivalent length of the lateral (emitter barb loss), f_e, for the micro-tube emitters is found in Fig. 18.

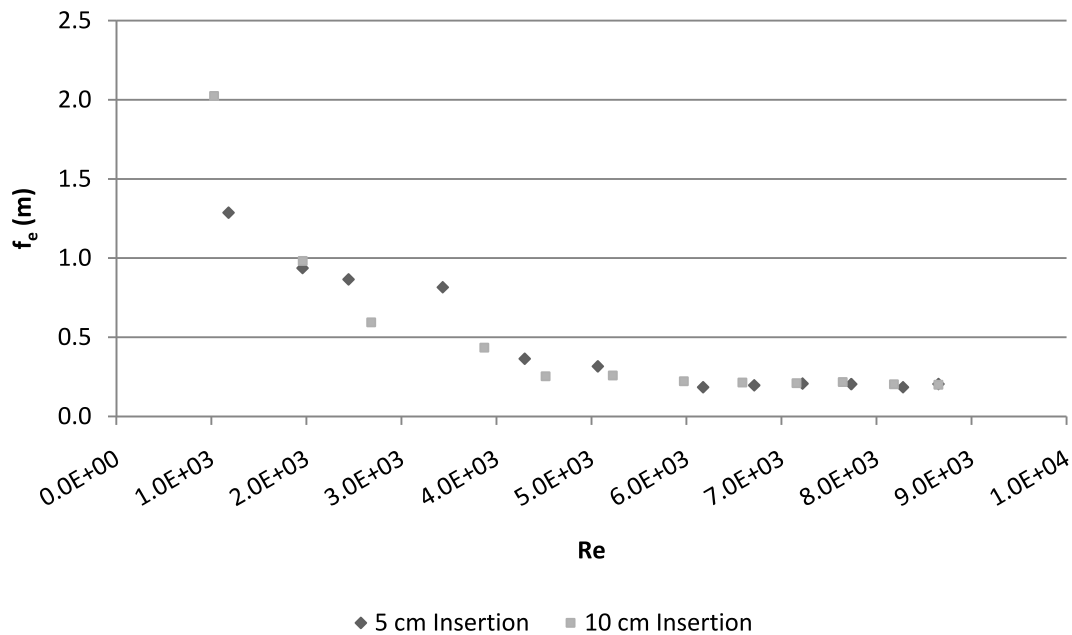

Fig. 18. Measured emitter connection loss expressed as an equivalent length of lateral for micro-tube emitters

Measurements were taken with the micro-tubes inserted to 5 cm and 10 cm. The average coefficient of variation of measured flows for the 5-cm and 10-cm insertion data was 0.61% and 0.56%, respectively. The values of f_e begin to stabilize as the flow becomes more turbulent, becoming near constant for $R_e > 6{,}000$. Above this value, the average f_e for the micro-tubes inserted to 5 cm was 0.20 m, with a standard deviation of 0.01, and a coefficient of variation of 5%. The average f_e for the micro-tubes inserted to 10 cm was 0.21 m, with a standard deviation of 0.01, and a coefficient of variation of 4%. Thus, micro-tube emitter insertions from 5 to 10 cm do not result in a significant difference in the barb loss.

Button Emitters

The measured emitter connection loss data for button emitters on two samples of lateral are presented in Fig. 19. The first sample was prepared in the afternoon, under relatively hot conditions (> 35°C). When the test was performed the following morning, it was observed that the lateral had contracted due to the cooler temperatures; thus, it had to be significantly stretched in order to be attached to the downstream tank. A second sample of lateral was tested to verify the results of the first sample. The same selection of button emitters was used in both samples.

The results of both samples manifested significant scatter; however, the values of f_e tend to decrease and stabilize somewhat as the flow becomes more turbulent. The peak f_e value between Reynolds numbers of 3,000 and 4,000 suggests the presence of a

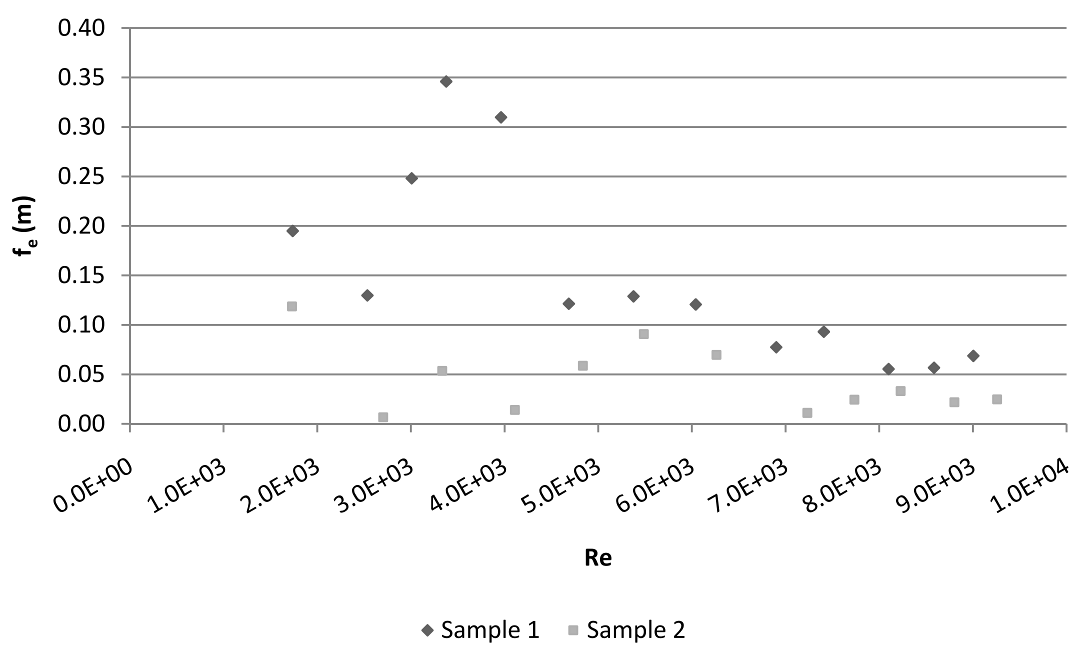

Fig. 19. Measured emitter connection loss expressed as an equivalent length of lateral for button emitters

transitional flow regime. Above Reynolds numbers of 4,000, the average f_e for the first sample was 0.09 m, with a standard deviation of 0.03, and a coefficient of variation of 33%. For the same range of Reynolds numbers, sample 2 yielded an average f_e of 0.04 m, with a standard deviation of 0.03, and a coefficient of variation of 72%. The overall average f_e was 0.06 m. The average coefficient of variation of measured button emitter flows was 0.41%.

Emitter Performance

The results of the emitter performance are reported below for each emitter type. The same sample of 250-μm wall thickness pre-punched lateral that was used for the friction loss testing was used for all emitter performance tests. The emitter spacing characteristics of the lateral are shown under "Sample 1" in Table E.1. The length of the lateral, equal to the distance from the lateral inlet to the last emitter, was 17.8 m. While the lateral had 44 pre-punched holes, two of the holes were unusable, and consequently plugged, because of tearing in the lateral wall that apparently occurred during manufacture.

The emitter flow through the pre-punched holes was measured first, and then the micro-tubes were inserted into the same lateral. Next, the micro-tubes were removed and the pre-punched holes were allowed to return to their original shape before the button emitters were inserted. Each emitter flow rate was measured three times for every test, and the average coefficient of variation of all measured emitter flow rates was less than 1%.

Pre-punched Holes

The head-discharge relationship of the pre-punched holes in the 250-µm wall thickness lateral is shown in Fig. 20. In this figure, the vertical clusters of data points represent the flow distribution of 42 emitters along the lateral for a given inlet pressure head. As the inlet head increases, the variation in both the emitter flow and pressure head along the lateral increases. A summary of the measured performance data of pre-punched holes is found in Table A.4. The average coefficient of variation of emitter pressure head along the lateral was 2%; the average *CvU* was 69.4%, which is barely in the acceptable range for low-cost drip irrigation systems.

For the emitter discharge in lph and the head in m, the average discharge coefficient, k_d, for pre-punched holes was 5.85 (equal to the average emitter flow rate at 1 m of head), and the average discharge exponent, x, was 0.58. The coefficient of

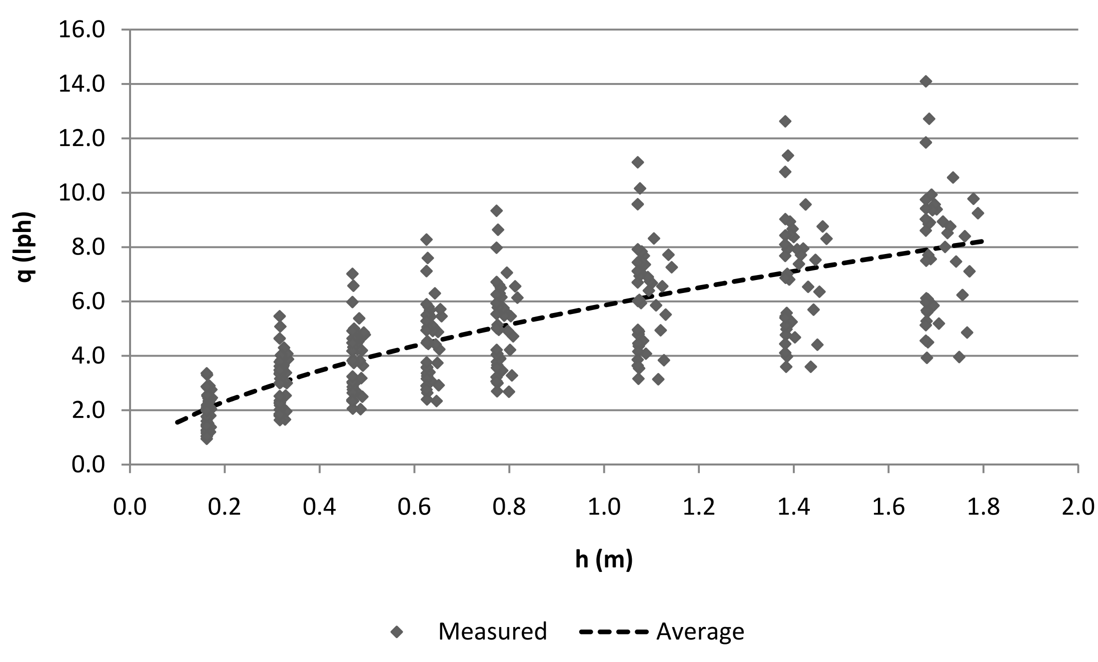

Fig. 20. Emitter head-discharge relationship for pre-punched holes

manufacturer's variation, v_m, was 0.31, which is "unacceptable" according to the American Society of Agricultural and Biological Engineers (ASABE) standards for line-source emitters (ASABE 2008).

Micro-tube Emitters

The head-discharge relationship of the micro-tube emitters, inserted to 5 cm, is found in Fig. 21. In this figure the six individual clusters of data points represent the emitter flow and head distribution of 42 emitters along the lateral for a given inlet pressure head. A summary of the measured data for the performance micro-tube emitters is found in Table A.5. The average coefficient of variation of emitter pressure head along the lateral was 6%. The average *CvU* was 92.8%, which is in the excellent range for low-cost drip irrigation systems.

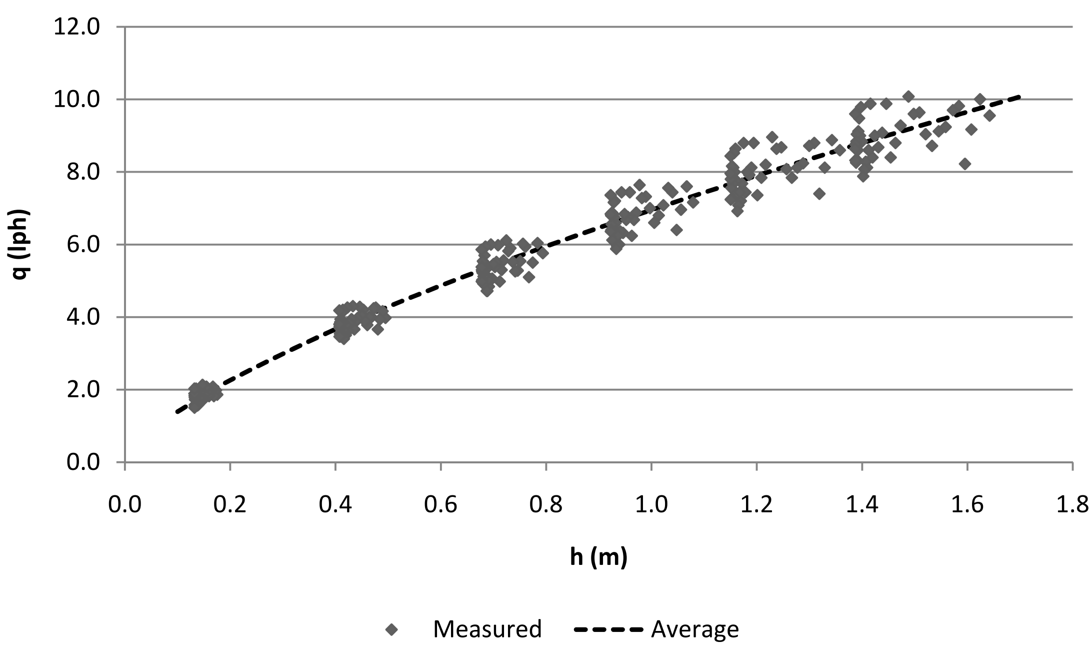

Fig. 21. Head-discharge relationship of micro-tube emitters

The average emitter discharge coefficient, k_d, was 6.96, and the average discharge exponent, x, was 0.70. The coefficient of manufacturer's variation, v_m, was 0.06, which is "good" according to ASABE standards for line-source emitters.

Equation (40) was used to estimate the emitter barb loss along the lateral of micro-tubes inserted to 5-10 cm in the emitter performance tests:

$$f_e = 4622.2 R_e^{-1.125} \tag{40}$$

Equation (40) was fit to the data in Fig. 18 ($R^2 = 0.9398$).

Button Emitters

The head-discharge relationship of the button emitters is shown in Fig. 22. In this figure, the vertical clusters of data points represent the flow distribution of 42 emitters along the lateral for a given inlet pressure head. Above 1 m of inlet pressure head, the

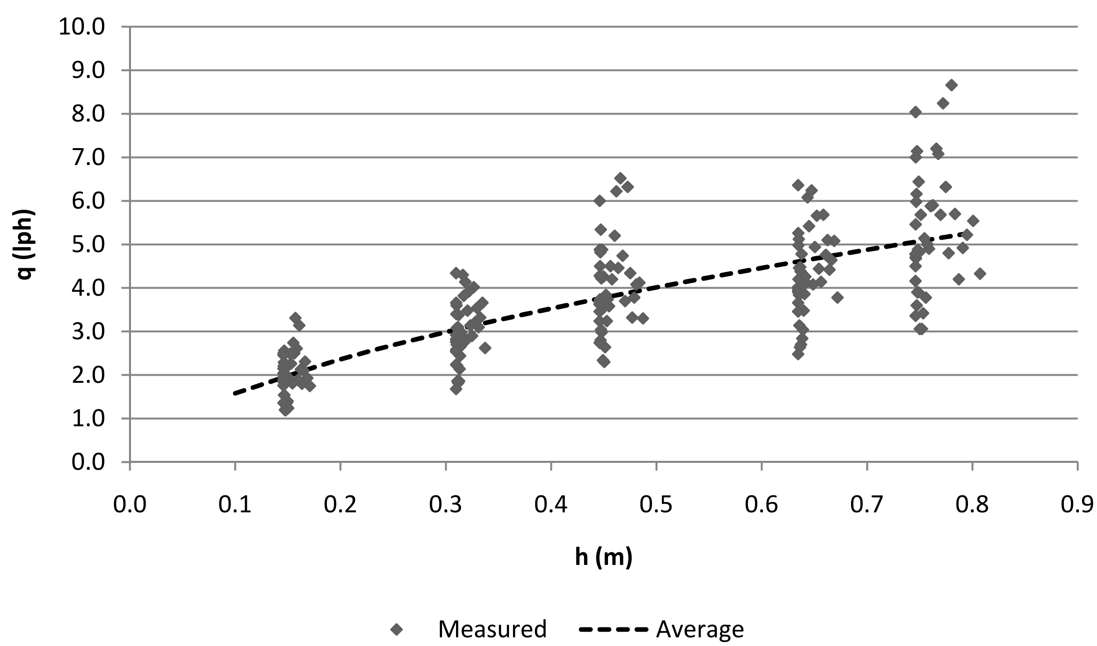

Fig. 22. Head-discharge relationship of the button emitters

emitter flow became very sporadic, and the flow wrapped around the lateral, shooting vertically up into the air, making flow measurement difficult (see Fig. 23). A summary of the measure data for the performance of button emitters is found in Table A.6. The average coefficient of variation of emitter pressure head along the lateral was 3%. The average *CvU* was 75.9%, which is acceptable for low-cost drip irrigation systems.

The average emitter discharge coefficient, k_d, was 6.00, and the average discharge exponent, x, was 0.58. The coefficient of manufacturer's variation, v_m, was 0.24, which is "marginal to unacceptable," according to ASABE standards for line-source emitters.

Due to the scatter of the emitter barb loss data in Fig. 19, an empirical equation could not be used to accurately estimate the equivalent length barb loss based on the Reynolds number. Instead, the barb loss of the button emitters along the lateral was estimated using the following criteria based on the data in Fig. 19: for $R_e < 3{,}000$, $f_e =$

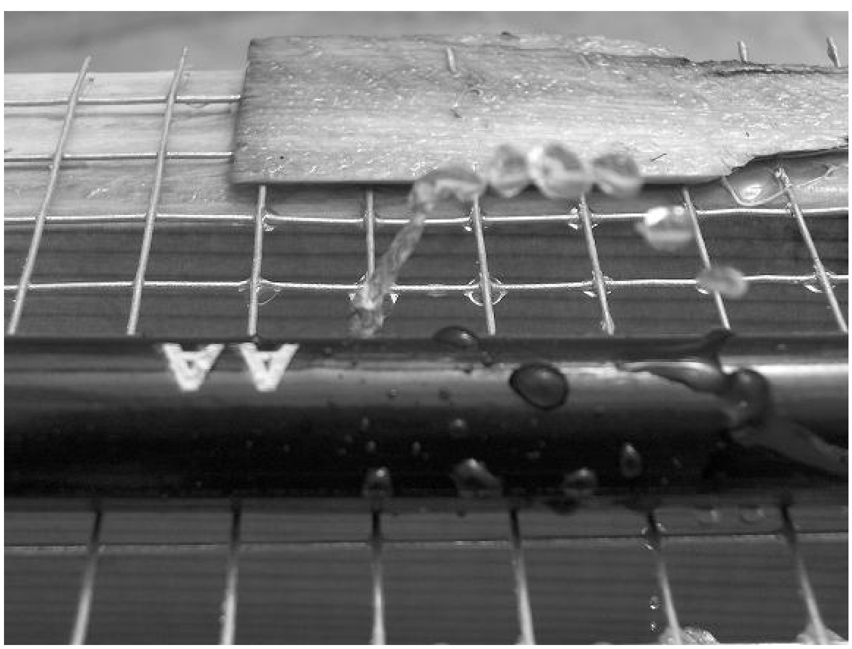

Fig. 23. Sporadic discharge from button emitters when the hydraulic head exceeded 1 m

0.15 m; for $3{,}000 < R_e < 6{,}000$, $f_e = 0.10$ m; and, for $R_e > 6{,}000$, $f_e = 0.06$. It is noted that small errors in the estimation of f_e will have a relatively insignificant effect on the overall barb loss. In fact, the largest overall barb loss measured for the entire lateral was only 1.4 cm (for an inlet pressure head of 1 m).

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The components of the IDEal drip irrigation system were tested under controlled laboratory conditions. Head loss in the grommet connector valves was measured, and the head loss due to friction in laterals of various wall thicknesses was characterized. The emitter connection loss was determined for button emitters, and micro-tube emitters inserted to lengths of 5 and 10 cm. The head-discharge relationship was described for pre-punched holes in the lateral, button emitters, and micro-tubes. The resulting coefficient of manufacturer's variation was calculated for each emitter type, and the coefficient of variation uniformity, *CvU*, was also calculated.

The head loss in the grommet connector valves was measured, and the valve loss coefficient, k_v, was calculated. The overall average k_v was 7.27, with a standard deviation of 1.50, and a coefficient of variation of 21%. Results are based on measurements from six randomly selected valves free of manufacturing debris. The removal of debris from the valve decreased the valve loss coefficient by 29% and reduced the coefficient of variation to half of the previous value. Neither air temperature nor stopcock orientation had a significant impact on valve performance. On average, the inside diameter of the hole through the stopcock was 34% (3.7 mm) less than the outlet inside diameter.

The measured and estimated friction loss for IDEal laterals of various wall thicknesses is shown in Fig. 24. The friction loss was estimated using the Darcy-Weisbach and Blasius equations based on a smaller effective diameter estimated from the

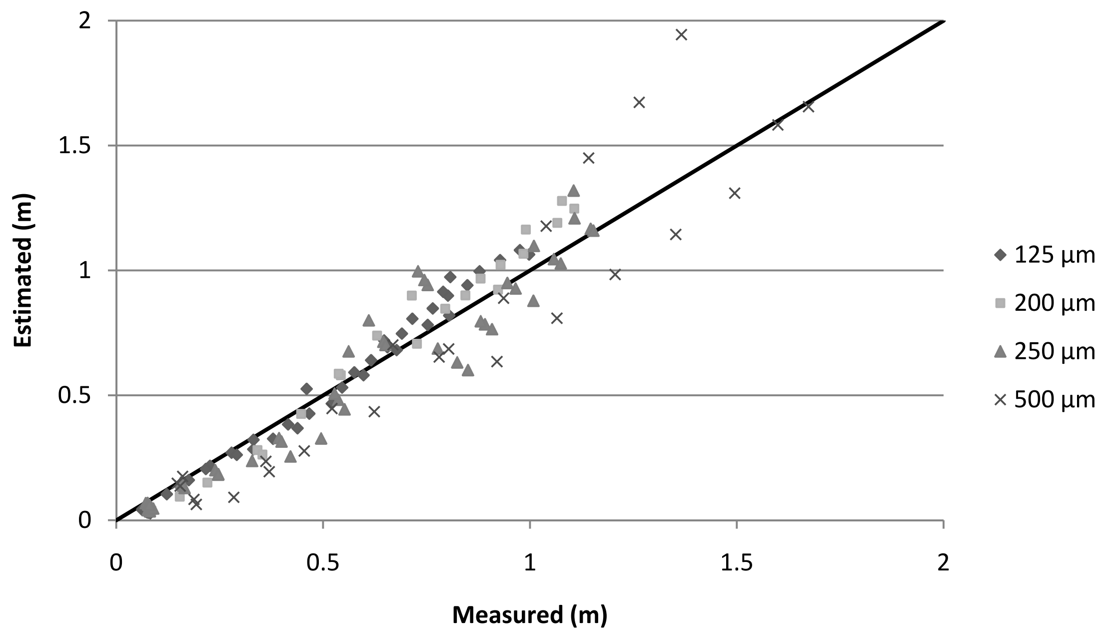

Fig. 24. Measured and estimated friction loss in IDEal laterals of various wall thicknesses

relationship of pressure head to lateral height. A summary of the friction loss estimation and the estimated effective diameters for IDEal laterals of various wall thicknesses is found in Table 4. The friction loss estimation was more accurate as the flow became more turbulent ($R_e > 4{,}000$). Effective diameters are shown for three ranges of inlet pressure head. Use of a smaller effective diameter than was measured improved the friction loss estimation. Disparity in the results of friction loss among different samples of the same wall thickness indicated a high degree of manufacturing variability. The variation was also evident in samples that came from the same roll of material (see Appendix D).

In the 500-µm sample friction loss estimation was more accurate when using $4R_h$ rather than the lateral height for the effective diameter. Laterals with thinner walls more

Table 4. Summary of Friction Loss Estimation in IDEal Lay-Flat Laterals

Wall thickness (μm)	Estimated Effective Diameter (mm) for Inlet Pressure Head Range < 0.5 m	0.5 - 1.0 m	1.0 - 2.5 m	% of measured h_f ($R_e > 4{,}000$)	r (overall)
125	15.5	16	16	103	0.9942
200	14.5	15.2	15.5	110	0.9939
250	13	15	15.5	102	0.9631
500	11.5	12.5	13.5	99	0.9402

fully inflate even at relatively low pressures, better approximating a circular cross section. The thicker wall requires a larger pressure in order to fully inflate. In the 500-μm sample the measured horizontal diameter, D_x, was on average more than twice the vertical diameter, D_y. In addition, the 500-μm sample showed greater sensitivity to temperature, which altered the lateral hydraulic characteristics.

The emitter connection loss expressed as an equivalent length of lateral, f_e, was calculated for button emitters, and micro-tubes inserted to 5 and 10 cm, using 250-μm wall thickness drip tape. The results for the button emitters showed significant scatter; however, above Reynolds numbers of 4,000 the results began to stabilize to a f_e value of 0.06 m. Little difference was found in the value of f_e for micro-tubes inserted to 5 and 10 cm. The results for each became near constant above Reynolds numbers of 6,000, converging to a value of 0.20 m and 0.21 m for 5 and 10-cm insertion, respectively. The value of f_e for pre-punched holes was assumed to be equal to zero.

A summary of the emitter characteristics of pre-punched holes, micro-tubes, and button emitters is shown in Table 5. The average discharge coefficients for each emitter type are shown based on the head in meters and the emitter flow in liters per hour, and

Table 5. Summary of IDEal Emitter Characteristics

Emitter Type	f_e (m)	k_d	x	ν_m	Avg. CvU (%)
Pre-punched hole	0	5.85	0.58	0.31	69.4
Micro-tube	0.21	6.96	0.70	0.06	92.8
Button	0.06	6.00	0.58	0.24	75.9

Note: For micro-tubes with ID = 1.5-1.8 mm and length of 15 cm

the average head-discharge relationship is shown in Fig. 25. The average *CvU* is based on a 17.8-m long lateral with 42 emitters.

The pre-punched holes had the highest coefficient of manufacturer's variation at 0.31, which is unacceptable according to ASABE standards. Consequently, the pre-punched holes on average exhibited the lowest *CvU* at 69.4%. The pre-punched holes had an average flow of 5.85 lph for a pressure head of 1 m, which was the lowest of the three emitter types tested. The micro-tubes displayed the best coefficient of

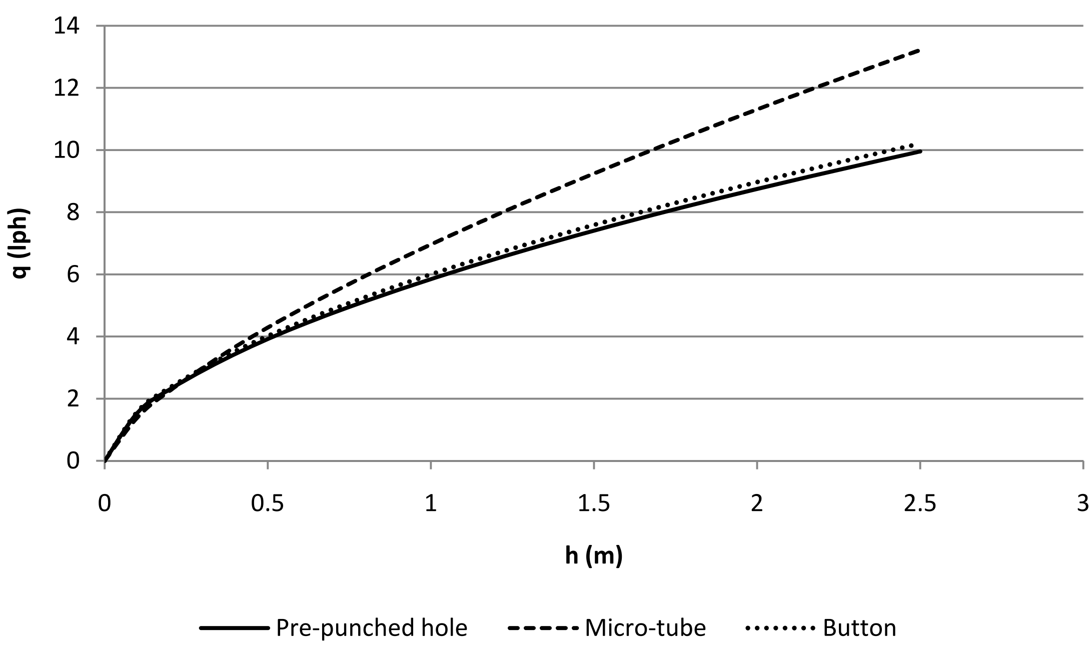

Fig. 25. Average emitter head-discharge relationship

manufacturer's variation at 0.06, which is good according to ASABE standards. Accordingly, the micro-tubes had the best average *CvU* at 92.8%, which is excellent for low-cost drip irrigation systems. The micro-tubes also displayed the highest average flow for 1 m of pressure head at 6.96 lph. The button emitters showed a slight improvement over the pre-punched holes with a coefficient of manufacturer's variation of 0.24 and an average *CvU* of 75.9%. The average emitter flow for button emitters at 1 m of head was 6.00 lph; however, flow became sporadic above 1 m of head.

The breakdown of measured head loss expressed as a percent of the inlet pressure head in the 17.8-m long lateral of 250-µm wall thickness with 42 emitters is shown in Table 6. On average, 17% of the inlet pressure head was lost in the connector valve, while only 6% was lost due to friction in the lateral. Micro-tube emitter barbs accounted for 8% of the inlet head lost. When using button emitters, only 2% of the inlet head was lost on average. Thus, the majority of the head loss in the system occurs in the connector valve. However, the amount of head loss due to friction and emitter barbs will increase as the length of the lateral increases.

Table 6. Average Measured Head Loss as a Percent of Inlet Pressure Head in a 250-µm Wall Thickness Lateral Using Various Emitter Types

Emitter Type	Valve	Friction	Emitter Barbs
Pre-punched hole	17%	5%	0%
Micro-tube	19%	6%	8%
Button	16%	6%	2%

Conclusions

Until now, IDEal drip irrigation system designers could only roughly estimate the hydraulic characteristics of the system components. The results of this research provide designers with the information necessary for creation of an efficient low-cost drip irrigation system. The reported values can replace previous guesses of the inputs for IDEal drip lateral design aides. In addition, observations made throughout testing can be used to improve system manufacturing.

Testing on the connector valves showed that the majority of the head loss in the system occurs in the valve. Due to a maximum-minimum difference of 5.11 and a coefficient of variation of 21% in the valve loss coefficient, system designs could significantly over- or under-estimate the actual head loss. The high head loss can be partially attributed to the hole through the stopcock, which was significantly smaller than the valve inlet and outlet inside diameters. In addition, the hollow stopcock causes more turbulence to occur, increasing the head loss. The high variation between valves indicates the need for improved quality control in manufacturing. However, if the amount of head loss can be reduced, the variation will not be as great a concern. The presence of manufacturing debris in the valve significantly reduces the flow, increases the head loss, and further increases the variability in the valve loss coefficient.

The fourth friction loss estimation method used a different (usually smaller) effective diameter to accurately estimate the friction loss in the lateral. Thus it is not necessary to create a new empirical equation for estimating the friction factor; the friction loss can be accurately estimated using standard friction loss equations based on the criteria for effective diameter according to the pressure head and wall thickness, as outlined in the previous section (see Table 4).

Variation between samples of lateral with the same wall thickness indicates the need for improvements in the manufacturing process and in quality control. Extreme variation found in the lateral wall thickness (see Appendix D) makes it more difficult to accurately estimate friction loss. Furthermore, because the lateral is sold by weight it means that the consumer may be getting less length than expected. The quality of the lateral is only as good as the minimum wall thickness, thus the consumer may not be getting sufficiently durable material. The high variation in the emitter spacing of the pre-punched lateral (see Appendix E) can have a significant impact on the overall system uniformity, and makes design of an effective system difficult.

The results of the friction loss tests in the 125, 200, and 250-µm wall thickness laterals supported the theory that the lateral cross-sectional area in the creases does not greatly impact the flow path diameter. However, the 500-µm wall thickness sample showed that use of the lateral height for the effective diameter drastically overestimated the measured friction loss; using four times the hydraulic radius for the effective diameter improved the friction loss estimation. Thus, it may be that this theory only applies when the lateral cross-section is sufficiently round (for example when $D_x/D_y < 2$).

The results of the emitter barb loss for button emitters showed significant scatter, which was in part caused by manufacturer's variation in the lateral, as well as the degree to which the lateral was stretched during testing. However, in the turbulent regime the values of f_e mostly varied between 5 and 10 cm, which is not a significant difference. For micro-tubes, the barb loss remained nearly constant for insertion lengths of 5 and 10 cm. Thus, the f_e value of 0.21 m can be safely used for design purposes when micro-tubes are inserted to between 5 and 10 cm.

Both the pre-punched holes and the button emitters had a coefficient of manufacturer's variation that was unacceptable. As a result, the *CvU* along the lateral was borderline acceptable. While the button emitter appeared to be an improvement over the pre-punched hole, the sporadic flows observed over 1 m of inlet head challenge that conclusion. In addition, the performance of the button emitter is dependent on the quality of the pre-punched hole, as the button uses the side of the hole to form the orifice. Rotating the button emitter in the hole will change the performance because the pre-punched holes were not perfectly circular. The puncturing of both sides of the lateral during punching and occasional tears in the pre-punched holes indicates the need for an improved method of punching holes in the lateral. The method of punching on the tested product was unknown;[1] however at the time of writing, testing was underway of a new method of punching using a laser to burn through one lateral wall, yielding a more uniform hole.

The micro-tube emitters manifested excellent uniformity. This is directly related to the fact that the coefficient of manufacturer's variation was good. However, the flow rate is relatively high, and the emitter discharge exponent of 0.70 means the discharge is more sensitive to pressure variation. This sensitivity will have a greater impact on the overall system uniformity when more laterals are used in series.

International Development Enterprises has developed a spreadsheet that uses various inputs such as lateral length, emitter spacing, inlet pressure head, lateral ID, lateral connection "k", and the emitter head-discharge characteristics to estimate the distribution of the emitter discharge along the lateral. Figure 26 shows the estimate from the IDEal drip lateral design spreadsheet compared to the measured results of the emitter performance tests using micro-tube emitters at 1 m of inlet pressure head. The inputs for

[1] It was most likely done either with a hot or cold needle, which was common at the time of testing.

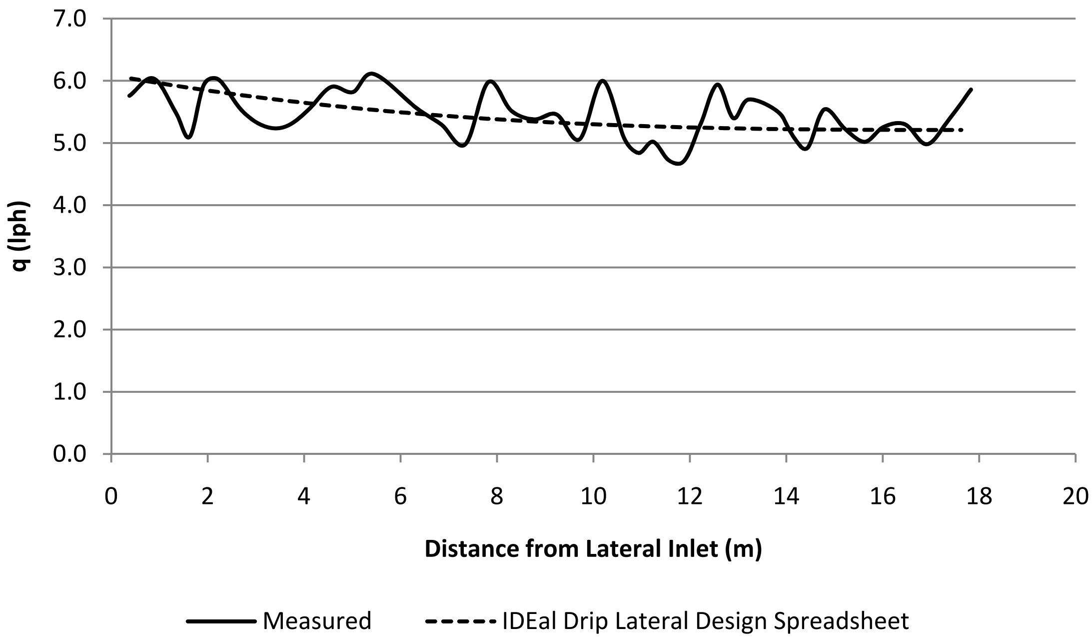

Fig. 26. Distribution of emitter discharge along the lateral. Measured values for an 18-m long lateral using micro-tubes at 1 m of inlet pressure head are compared to the estimate using the IDEal drip lateral design spreadsheet.

the spreadsheet are as follows (as recommended by the above results): $k_v = 7.3$; $f_e = 0.21$ m; lateral ID = 15 mm; connection ID (valve outlet ID) = 11 mm; emitter exponent, $x = 0.7$; emitter $k_d = 6.96$; emitter $v_m = 0.06$; and, emitter spacing[2], $S_e = 41$ cm. As expected, the results of the IDEal drip lateral design accurately approximate the measured results. The measured *CvU* was 92.9%, while the IDEal spreadsheet had an estimated *CvU* of 92.5%. Thus, the results of this study provide a set of criteria for use in IDEal drip lateral design.

[2] Equal to the average measured emitter spacing for this sample, with a coefficient of variation of 18%. The manufacturer's indicated emitter spacing was unknown. See Appendix E.

Limitations

The valve loss coefficient, k_v, takes into account both the entrance losses from the upstream tank and the losses through the valve. However, in practice the entrance loss to the valve will be different because the valve is designed to connect to a lay-flat manifold, not a tank. Thus, the valve will protrude perpendicularly into the manifold, causing additional loss at the lateral-manifold connection.

The effect of air and water temperature on the lateral and the corresponding head losses remains uncharacterized. Air temperature and solar radiation fluctuations caused the lateral to stretch and contract, affecting the behavior of the lateral cross section to pressure variations. The degree to which the lateral is stretched during installation may also affect the hydraulic characteristics of the lateral.

In friction loss tests, the lateral diameter was assumed constant for the entire length of the lateral. However, this was not always the case, especially in laterals of thicker walls when tested under relatively large pressure gradients; the diameter was larger at the inlet than the outlet. To compensate for this, the diameter was measured at the midpoint of the lateral.

For emitter performance tests, emitters were placed on the bottom of the lateral. In the field, the emitters are placed on the top of the lateral. Flow characteristics of pre-punched holes and button emitters were susceptible to change as the weight of the lateral occasionally pressed down on the emitter outlet. This generally occurred when the emitter was not directly over a gap in the wire mesh. This problem was solved by placing shims on either side of the emitter.

Through field observations it was discovered that micro-tubes are typically longer than the tested length of 15 cm. In addition, the emitters are tied in loops to prevent the emitter outlet from laying in the soil. How these factors affect the head-discharge relationship is unknown. However, variation in the inside diameter, rather than the length, of the micro-tube will have a greater impact on emitter performance.

Recommendations

The recommendations from this research are based on IDEal system components supplied in May 2008. Since then, IDE has continued to modify and improve the systems (partly in response to early results from this research); thus, some of the recommendations will no longer apply. The difficulty in the design of low-cost drip irrigation systems for small plots is in determining how to create an effective and efficient system while maintaining low system costs. It is likely that many of these recommendations will not significantly increase system costs. Other recommendations require further research to determine their feasibility. The recommendations are summarized in bulleted form in the following section. Additional recommendations from the field observations regarding manufacturing, installation, and operation and maintenance are found at the end of Appendix G.

Testing on the connector valves revealed high head loss and manufacturer's variation. Head loss in the valve can be reduced (if a low head loss is desired; for example, in the case of laterals with zero slope) in several ways. A solid, rather than hollow, stopcock would reduce the turbulence that results from having an open chamber in the center of the valve. Also, the inside diameter of the hole through the stopcock should be equal to the valve inlet and outlet inside diameters in order to eliminate numerous expansions and contractions, which contribute to head loss. A constant valve ID will also reduce clogging in the valve, which occurs when a valve is used before the system filter (as observed in field observations). If the amount of head loss can be reduced, the manufacturer's variation will not be as great a concern.

Removal of debris leftover from the valve manufacturing process will decrease the head loss and the variation. However, this can be a tricky process and often requires the use of a special tool, for example a knife or needle-nosed pliers. This could be accomplished by the system manufacturer, or by the installer. All of these changes could probably be accomplished with little increase in the overall cost of the valve.

The head loss of connector valves when connected to the mainline or manifold is unknown. Also, the friction loss in IDEal mainlines and manifolds have not been quantified. The determination of these two factors is required to accurately design a complete system.

The manufacturing variability in the lateral wall thickness must be reduced to allow for accurate friction loss estimation. The criteria for estimating the effective lateral diameter, as outlined above in Table 4, provide inputs for relatively accurately estimating the friction loss in IDEal laterals using standard equations. However, as the wall thickness increases, additional factors arise that affect the accuracy of these criteria. The physical and hydraulic response of the lateral to both air and water temperature will contribute to variation in the experimental results, as will the degree to which the lateral is stretched in installation.

Due to an unacceptably high manufacturer's variation, pre-punched holes should not be selected as an emitter type in irrigation system design. The button emitters do not provide a significant improvement in uniformity over the pre-punched holes. Button emitters use part of the pre-punched hole to form the orifice, thus they are dependent on the quality of the pre-punched hole. Thus, the performance of the button emitters will improve as the high variation in the pre-punched holes is reduced. This high variation may be inherent in the punching process, or due to variation in lateral wall thickness, or both. The high variation in the emitter spacing of the pre-punched holes further contributes to the need for investigation into improvements in the punching process.

At this point, micro-tube emitters represent the best option for the emitter type in IDEal drip systems, and the head-discharge relationship defined in this study can confidently be used in system design. From the results of the field study, clogging is manageable with regular maintenance and is further outlined in the "Recommendations" section of Appendix G. In practice, micro-tubes are longer than 15 cm, and they are tied in loops when installed. How this affects the emitter performance is unknown.

Summary

The recommendations from this study are summarized below.

Connector Valves

- Solid stopcock (if minimal head loss is desired)
- Constant valve inside diameter
- Remove manufacturing debris

Laterals

- Friction loss can be accurately estimated using standard equations and the criteria for estimating effective lateral diameter as outlined in Table 4
- Improve manufacturing quality control in diameter and longitudinal and circumferential thickness

Emitters

- Micro-tubes are the emitter of choice among the tested alternatives, and the discharge coefficients of k_d = 6.96 and x = 0.70 for head in m and flow in lph should be used in design for micro-tubes with ID of 1.5-1.8 and length of 15 cm
- Improve pre-punched hole roundness, diameter, and spacing uniformity

Future Research

- Head loss of connector valves when connected to the mainline or manifold
- Friction loss in IDEal mainlines and manifolds, filters, and system valves
- Investigate manufacturing process to decrease variation in:
  - Lateral wall thickness
  - Pre-punched holes
  - Emitter spacing
- Emitter performance of micro-tubes of different lengths and inside diameters
- Emitter performance of new types of pre-punched holes
- Effect of time-lag (Appendix F) on overall system uniformity

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APPENDICES

APPENDIX A. Additional Tables

Table A.1. Flow Rates in lps for Valves at Various Hydraulic Heads

Valve #	Head (m)				
	0.5	1	1.5	2	2.5
1	0.10	0.14	0.17	0.19	0.22
2	0.11	0.15	0.19	0.21	0.24
3	0.12	0.17	0.20	0.24	0.26
4	0.10	0.14	0.17	0.20	0.22
5	0.11	0.16	0.19	0.22	0.25
6	0.10	0.14	0.18	0.20	0.23
Average	0.11	0.15	0.18	0.21	0.24
sd	0.01	0.01	0.01	0.02	0.02
ν	8%	8%	8%	7%	7%

Table A.2. Inside Diameters of Connector Valves

Valve #	Inlet ID (mm)	Outlet ID (mm)	min ID (mm)
1	10.1	11.2	7.1
2	10.3	11.1	7.5
3	10.1	10.9	7.6
4	10.3	11.2	7.2
5	10.3	11.1	7.5
6	10.3	11.0	7.3
Average	10.2	11.1	7.4
sd	0.10	0.12	0.20
ν	0.01	0.01	0.03

Note: min ID *is the minimum inside diameter of the hole through the stopcock*

Table A.3. Flow Rate at Various Heads in Valve 6 Before and After Debris Removal

H (m)	Q (lps)		Increase
	With Debris	Without Debris	
0.5	0.09	0.10	17%
1.0	0.12	0.14	17%
1.5	0.15	0.18	16%
2.0	0.18	0.20	16%
2.5	0.20	0.23	16%

Note: Increase *is the amount of flow rate increase caused by removing manufacturing debris*

Table A.4. Summary of Measured Data for Performance of Pre-punched Holes

H_{in} (m)	Q_s (lph)	q_a (lph)	h_a (m)	ν (h)	CvU (%)	h_f total (m)	h_{fe} total (m)	k_v loss (m)	K_r loss (m)
0.2	83.6	1.99	0.16	2%	68.1	0.011	0.000	0.026	0.001
0.4	130.9	3.12	0.32	2%	69.6	0.019	0.000	0.063	0.002
0.6	164.6	3.92	0.48	2%	69.7	0.028	0.000	0.100	0.003
0.8	192.4	4.58	0.63	2%	69.6	0.034	0.000	0.136	0.004
1.0	217.0	5.17	0.78	2%	69.5	0.048	0.000	0.173	0.006
1.4	257.5	6.13	1.09	2%	69.3	0.077	0.000	0.244	0.008
1.8	293.6	6.99	1.40	2%	69.5	0.093	0.000	0.317	0.010
2.2	326.0	7.76	1.70	2%	69.5	0.118	0.000	0.391	0.013

Note: ν (h) *is the coefficient of variation of emitter pressure head*

Table A.5. Summary of Measured Data for Performance of Micro-tube Emitters

H_{in} (m)	Q_s (lph)	q_a (lph)	h_a (m)	ν (h)	CvU (%)	h_f total (m)	h_{fe} total (m)	k_v loss (m)	K_r loss (m)
0.2	76.7	1.83	0.15	9%	91.0	0.010	0.035	0.022	0.001
0.6	162.4	3.87	0.43	6%	93.3	0.036	0.057	0.097	0.003
1.0	227.9	5.43	0.71	5%	92.9	0.056	0.070	0.191	0.006
1.4	285.7	6.80	0.96	5%	93.1	0.085	0.082	0.300	0.010
1.8	336.8	8.02	1.21	5%	93.2	0.124	0.097	0.417	0.014
2.2	377.6	8.99	1.46	5%	93.4	0.161	0.110	0.525	0.017

Note: ν (h) *is the coefficient of variation of emitter pressure head*

Table A.6. Summary of Measured Data for Performance of Button Emitters

H_{in} (m)	Q_s (lph)	q_a (lph)	h_a (m)	ν (h)	CvU (%)	h_f total (m)	h_{fe} total (m)	k_v loss (m)	K_r loss (m)
0.2	84.5	2.01	0.15	5%	75.6	0.020	0.007	0.026	0.001
0.4	126.3	3.01	0.32	3%	77.6	0.022	0.008	0.059	0.002
0.6	170.1	4.05	0.46	3%	74.5	0.034	0.010	0.106	0.004
0.8	181.8	4.33	0.64	2%	77.9	0.031	0.009	0.122	0.004
1.0	222.0	5.28	0.76	2%	73.9	0.053	0.014	0.181	0.006

Note: ν (h) *is the coefficient of variation of emitter pressure head*

APPENDIX B. Photographs of the Laboratory Setup and Experimental Work

Fig. B.1. Runway construction. The lateral was constructed in 3-m sections.

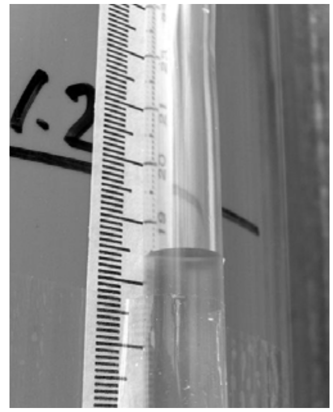

Fig. B.2. Tank piezometers. Each tank was fitted with a piezometer for water level measurement.

Fig B.3. Volumetric method for flow measurement

Fig. B.4. Upstream tank with lateral connected

Fig. B.5. Valve testing

Fig B.6. Lateral cross-section measurement using calipers

Fig. B.7. Micro-tube emitter plug

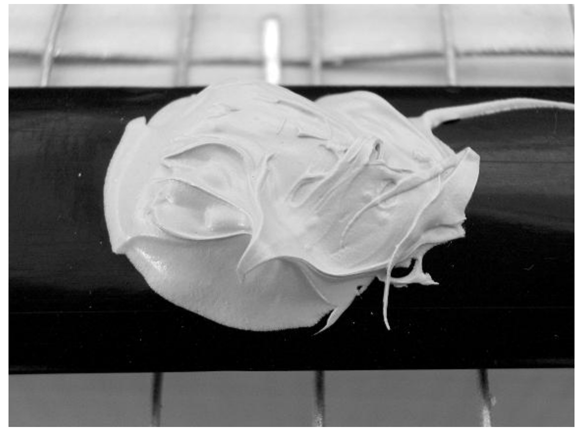

Fig. B.8. Button emitter plug

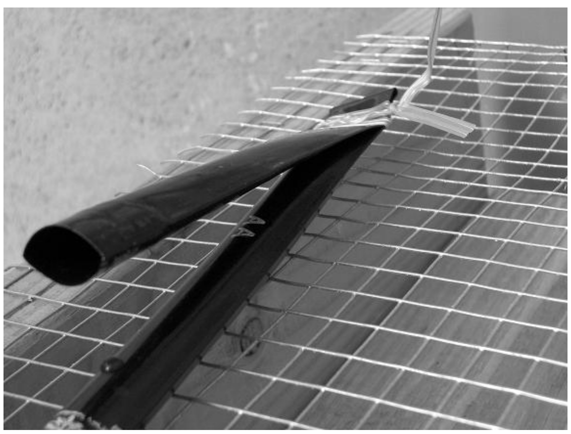

Fig. B.9. Lateral end plug by folding the lateral

Fig. B.10. Micro-tube emitter discharge

Fig. B.11. Button emitter discharge

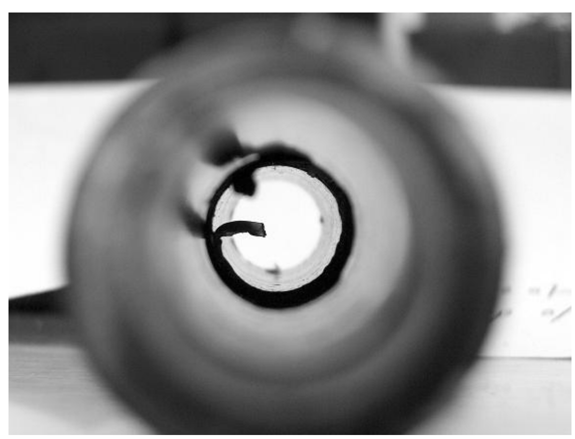

Fig. B.12. Valve chamber debris before cleaning

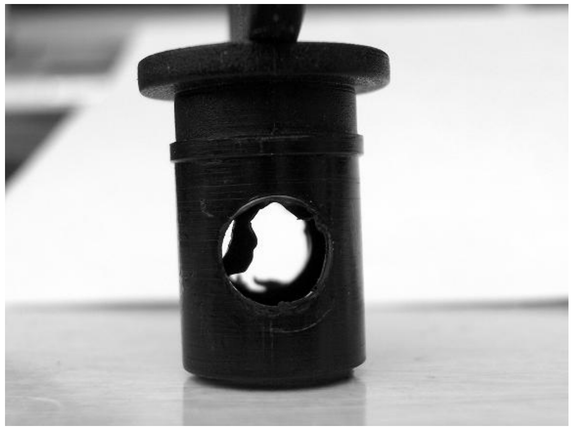

Fig. B.13. Valve stopcock debris before cleaning

APPENDIX C. Additional Figures

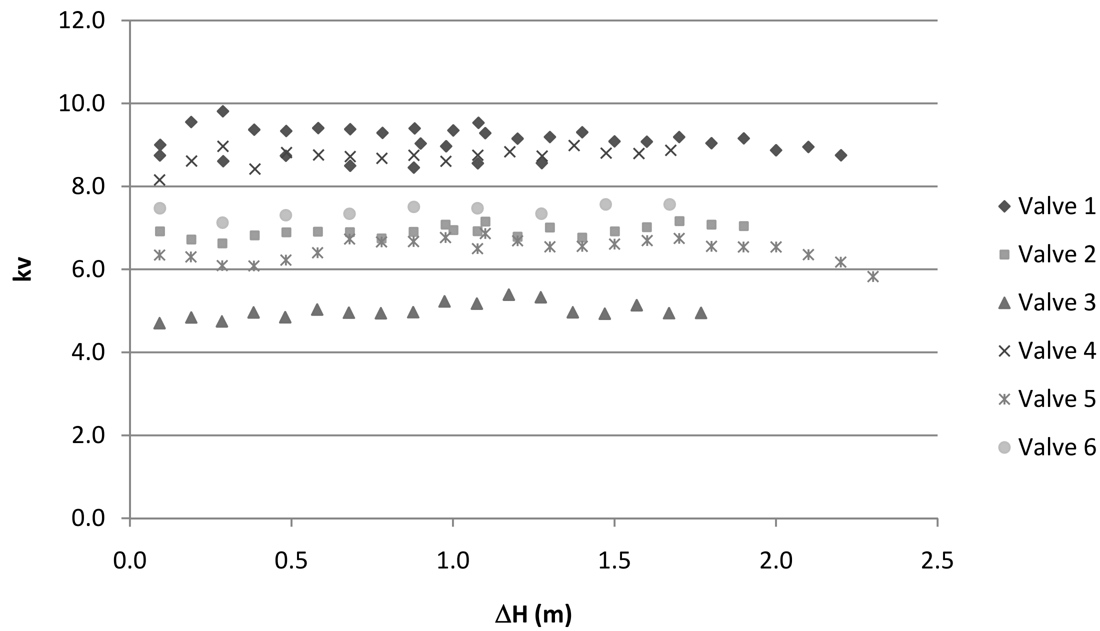

Fig. C.1. Valve loss coefficients for six connector valves

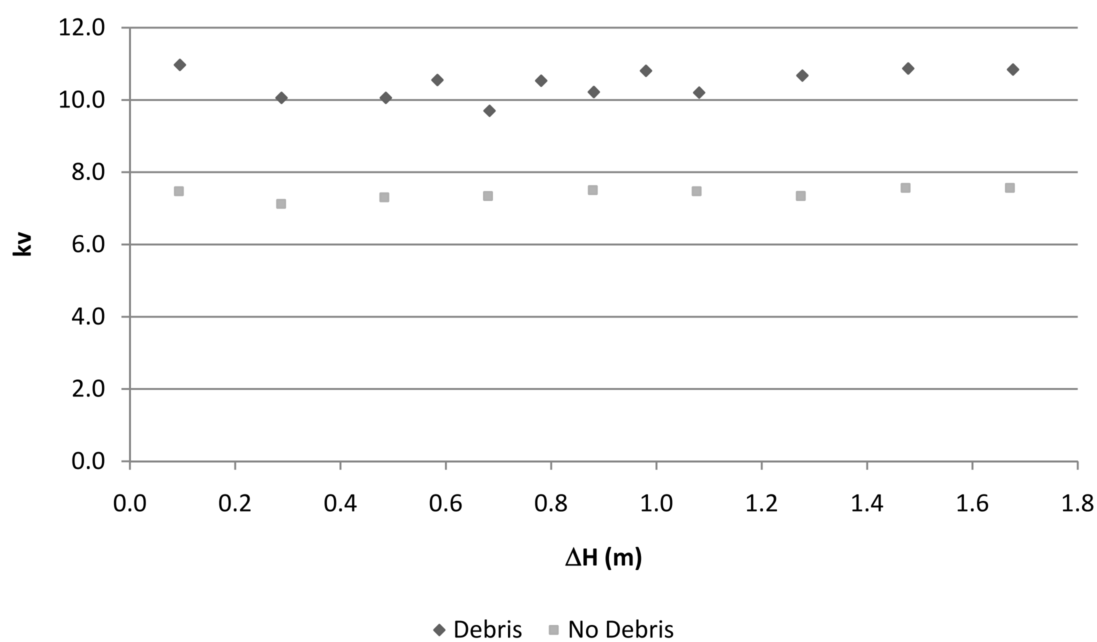

Fig. C.2. Effect of manufacturing debris on the valve loss coefficient of valve 6

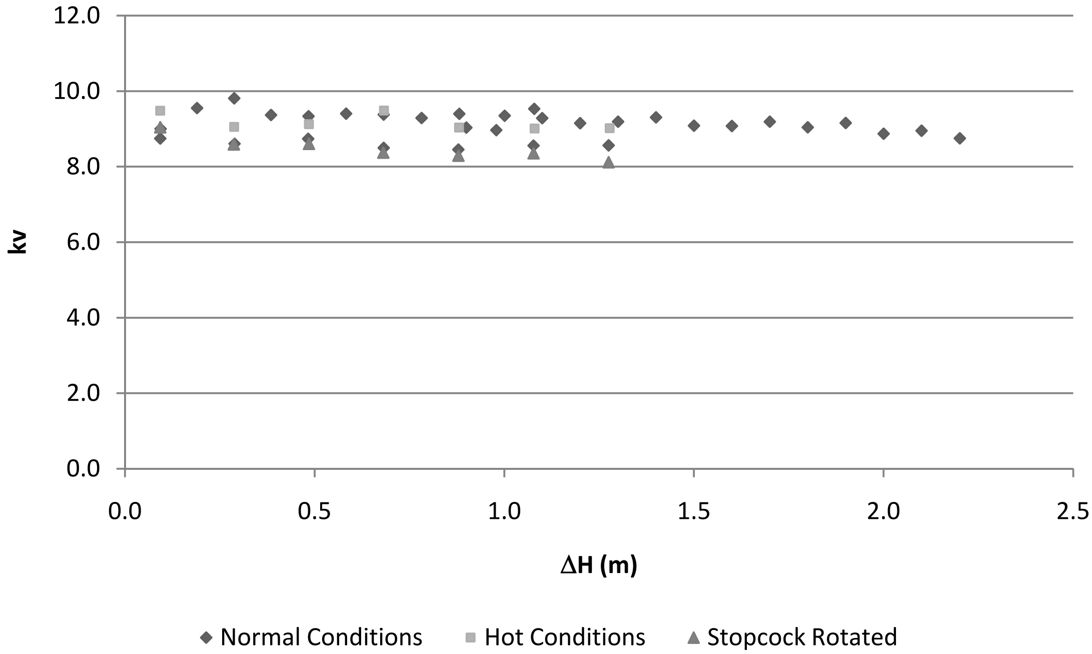

Fig. C.3. Valve loss coefficients for valve 1 under various conditions

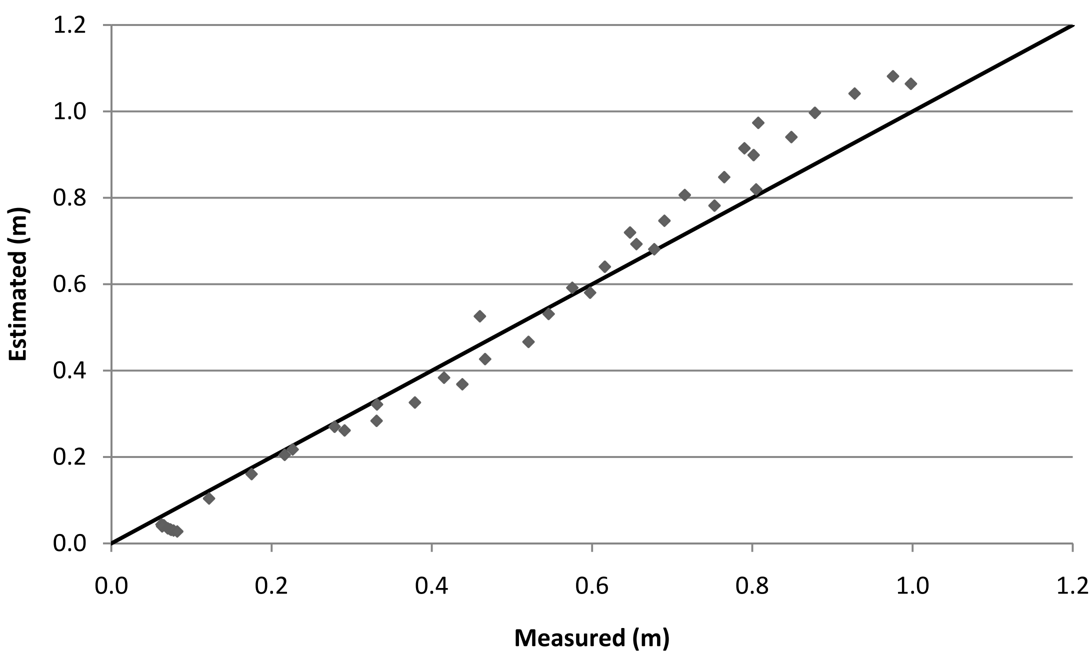

Fig. C.4. Measured and estimated friction loss in the 125-µm wall thickness lateral

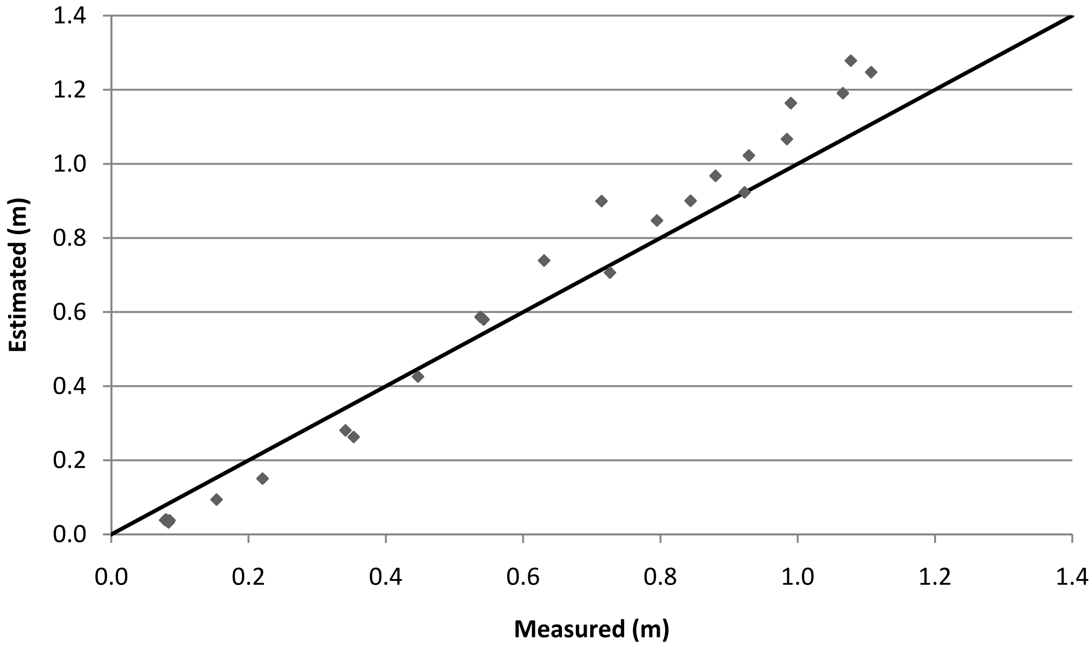

Fig. C.5. Measured and estimated friction loss in the 200-µm wall thickness lateral

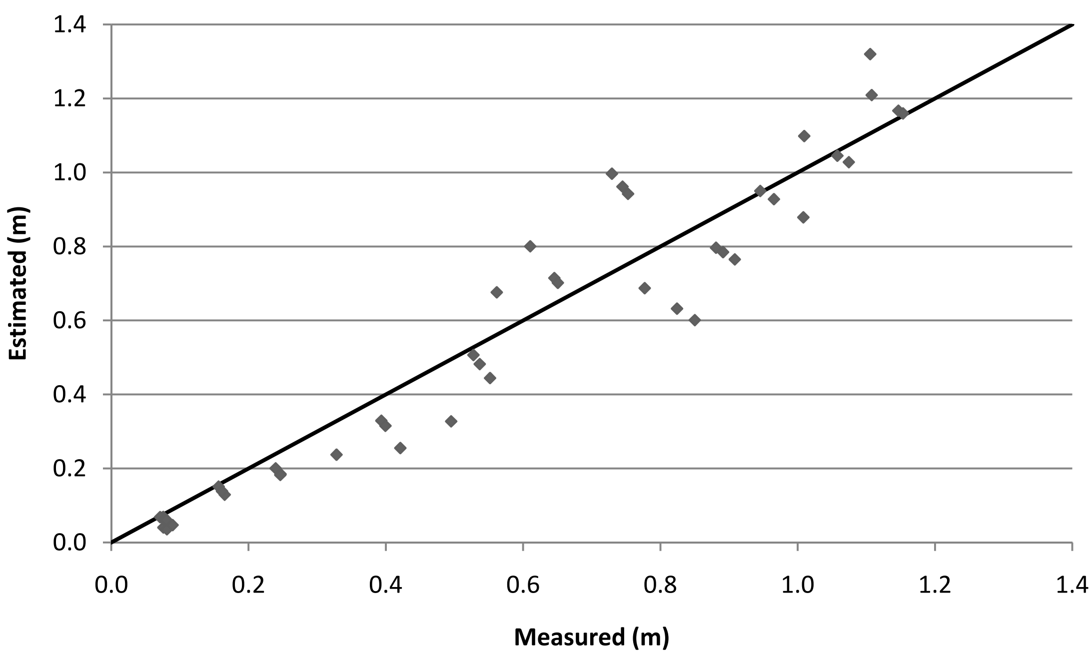

Fig. C.6. Measured and estimated friction loss in the 250-µm wall thickness lateral

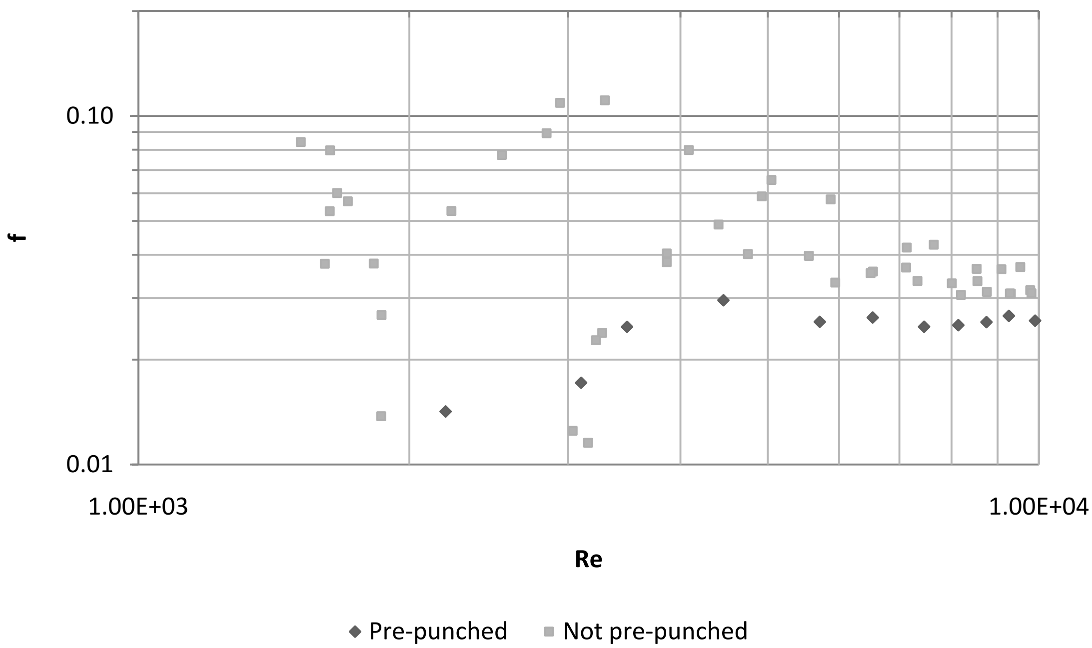

Fig. C.7. Measured friction factor and Reynolds number in the pre-punched 250-µm wall thickness lateral

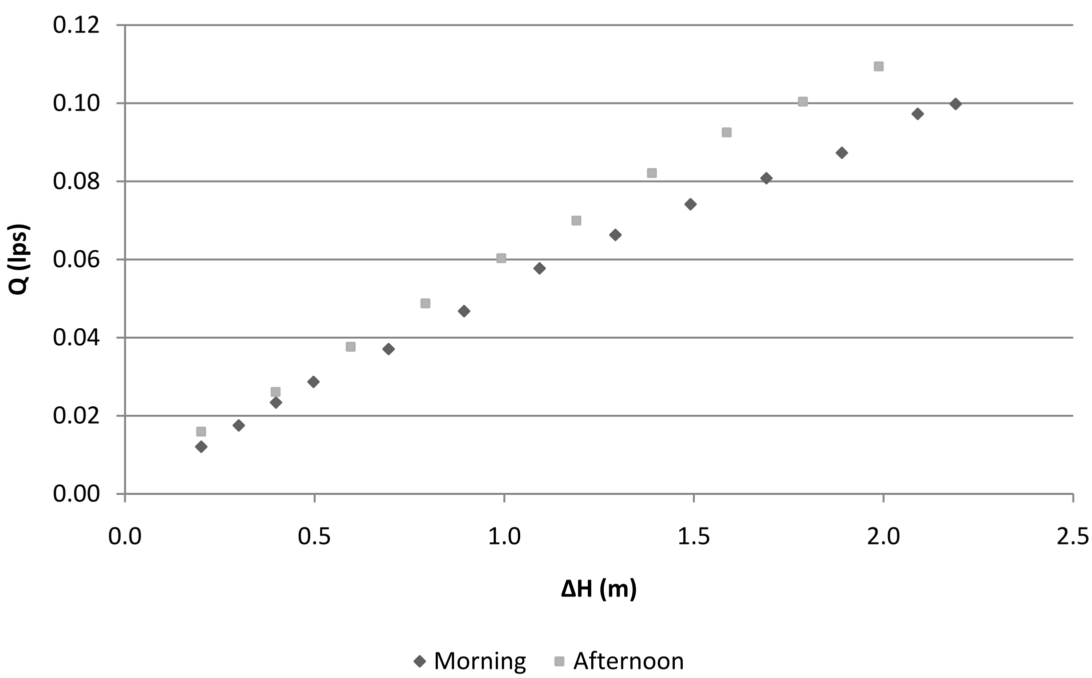

Fig. C.8. Measured head-discharge data for the 500-µm wall thickness lateral.

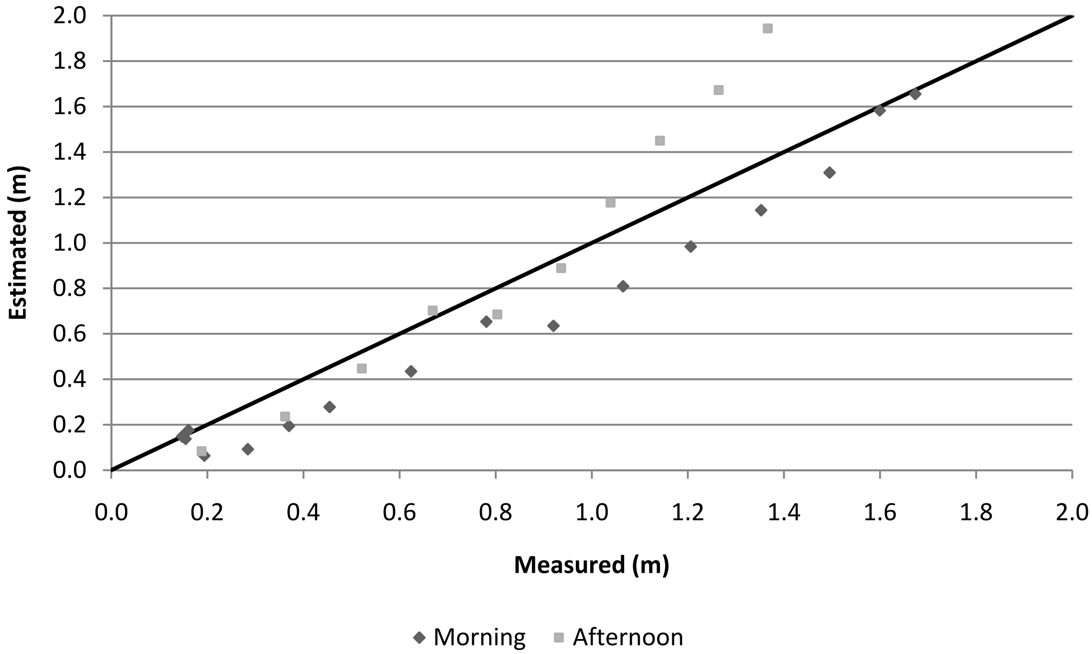

Fig. C.9. Measured and estimated friction loss in the 500-μm wall thickness lateral

APPENDIX D. Lateral Wall Thickness Study

Objective

During testing inconsistencies were found in the lateral wall thickness, specifically in 200 μm sample. The following measurements were taken in order to determine the variation in the wall thickness of the IDEal lateral drip tape.

Methodology

A 1-kg roll of 200-μm wall thickness IDEal lateral drip tape was obtained from a drip kit supplied to IDE-Ethiopia. The roll was cut into four 18.4-m lengths, which was the length of lateral required to fit the testing apparatus for the friction loss tests. The remaining 12 m was cut into one meter sections. The wall thickness was measured at the end of each section in order to obtain the variation of wall thickness along the length of an entire roll of drip tape. For each section, measurements were taken at six locations around the perimeter of the lateral cross-section to check for uniformity around the cross-section. The measurement locations were identified using "O'clock" notation. The lay-flat width of the lateral, including wall thickness, was also measured at the beginning of each section. A digital caliper with 0.01 mm resolution was used for all measurements. Measurements were taken at the UWRL greenhouse. Average air temperature during testing was 34° C.

Results and Discussion

The lateral wall thickness results are shown in Table D.1. The average, standard deviation, and coefficient of variation for the wall thickness around the cross-section for

Table D.1. Measured Wall Thickness for 200-μm IDEal Lateral

Sample #	Wall Thickness (mm) at O'Clock Position						Avg. (mm)	sd	ν (%)
	12	2	4	6	8	10			
1	0.15	0.14	0.26	0.31	0.26	0.20	0.22	0.07	30.8
2	0.16	0.18	0.30	0.32	0.29	0.20	0.24	0.07	28.7
3	0.14	0.13	0.25	0.28	0.25	0.19	0.21	0.06	30.4
4	0.15	0.15	0.26	0.30	0.26	0.20	0.22	0.06	28.6
5	0.15	0.16	0.27	0.29	0.25	0.19	0.22	0.06	27.2
6	0.16	0.17	0.28	0.31	0.27	0.19	0.23	0.06	27.9
7	0.16	0.18	0.28	0.32	0.29	0.20	0.24	0.07	27.9
8	0.15	0.17	0.28	0.31	0.28	0.20	0.23	0.07	28.8
9	0.17	0.20	0.30	0.35	0.30	0.21	0.26	0.07	27.9
10	0.15	0.17	0.27	0.29	0.26	0.20	0.22	0.06	25.9
11	0.16	0.18	0.28	0.33	0.30	0.20	0.24	0.07	29.2
12	0.16	0.16	0.26	0.31	0.28	0.19	0.23	0.07	28.7
13	0.16	0.19	0.28	0.31	0.28	0.20	0.24	0.06	25.7
14	0.15	0.16	0.26	0.29	0.27	0.20	0.22	0.06	27.0
15	0.16	0.17	0.25	0.30	0.28	0.19	0.23	0.06	26.5
Average	0.16	0.17	0.27	0.31	0.27	0.20	0.23	0.06	28.1
St. Dev.	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.00	0.0
Var. (%)	4.8	10.9	5.8	5.8	6.0	3.0	5.3	6.7	5.3

each section are reported. In addition, the average wall thickness at each position around the cross-section for the entire roll is reported. The average wall thickness for the entire roll was 230 μm with a coefficient of variation of 5.3% (10 μm). The average coefficient of variation in the wall thickness around the cross-section was 28.1% (60 μm). The manufacturer's stated wall thickness is 200 μm, plus or minus 5 μm. The average measured wall thickness was 15% greater than the indicated value.

The variation in wall thickness was also spotted visually. Figure D.1 shows manufacturing defects in the lateral wall at two locations along the length. Defects were generally raised portions of material that created a thick spot in the lateral wall.

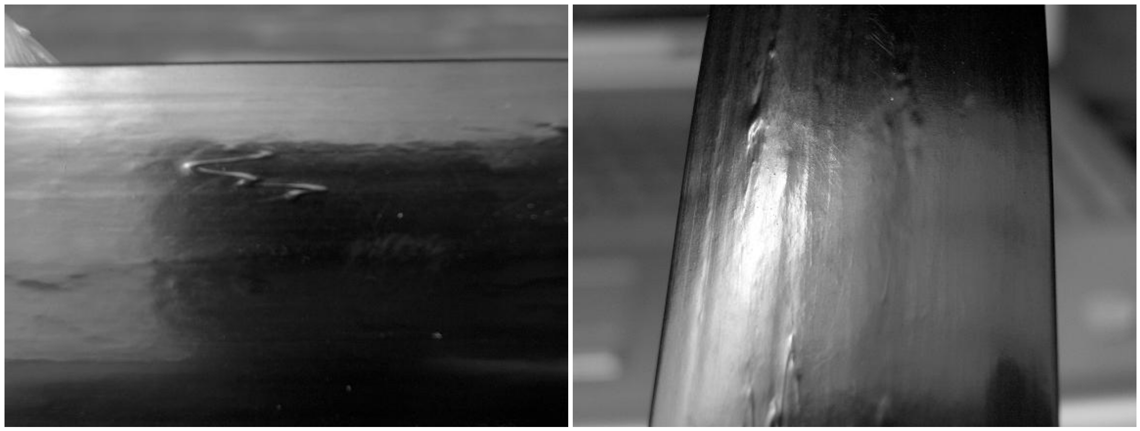

Fig. D.1. Defects in the lateral wall. Flaws or blemishes can be seen in both pictures that show extra material from the manufacturing process which formed ridges or thick spots in the lateral wall.

The total length of the 1 kg roll was 85.6 m. The results of the lay-flat width measurements are shown in Table D.2. The average lay-flat width for the roll was 26.6 mm, with a coefficient of variation of 2% (0.5 mm). The stated lay-flat width is 26.5 mm, plus or minus 0.5 mm.

Conclusions

The results show that the average wall thickness for this sample was 15% greater than indicated. Because drip tape is sold by weight, this means the consumer receives less overall length than advertised. The variation in the wall thickness was greater than stated. Defects in the material were also visually spotted. While the results are not a statistically representative sample of all manufactured drip tape, they indicate the need for improved quality control. In addition, the data suggest that improvement of the manufacturing process may be necessary.

Table D.2. Lay-Flat Width of 200-μm Wall Thickness IDEal Lateral

Sample #	Width (mm)	Sample Length (m)
1	26.0	18.4
2	25.7	18.4
3	26.9	18.4
4	26.9	1.0
5	27.3	1.0
6	27.1	1.0
7	27.0	1.0
8	26.3	1.0
9	27.3	1.0
10	26.5	1.0
11	27.3	1.0
12	26.7	1.0
13	26.4	1.0
14	25.7	1.0
15	26.6	1.0
Average	26.6	
sd	0.5	
ν	2.0%	

APPENDIX E. Emitter Spacing Study

Introduction

Four 18.4-m long samples of 250-µm wall thickness pre-punched lateral were used throughout laboratory testing. The variation in the emitter spacing for all samples is reported. The quality of the pre-punched holes was also observed.

Methodology

The emitter spacing was measured for four 18.4-m long samples of 250-µm wall thickness pre-punched lateral. The samples all came from the same roll of material, and thus the same manufacturer. The emitter spacing was not specified by the manufacturer.

Results and Discussion

The summary data for emitter spacing of the four samples is presented in Table E.1. The maximum and minimum emitter spacing for all measurements was 50.8 and 22.7 cm, respectively, which yields a maximum difference of 28.1 cm. This reflects a maximum and minimum of 62 and 44 emitters for an 18.4-m long sample, a difference of 18 emitters. The overall average was 34.5 cm, with a standard deviation of 4.9, and a coefficient of variation of 14%.

Several of the pre-punched holes were observed as tears in the lateral wall. This caused leaks to occur at the emitter-lateral connection. In addition, in many cases the hole had been punched through both walls of the lateral, which caused leaks on the back-side of the pre-punched hole.

Table E.1. Summary Data for Emitter Spacing in Four Samples of 250-µm Wall Thickness Pre-punched Lateral

		Emitter Spacing, S_e (cm)					
Sample	N_e	Max	Min	Diff.	Average	sd	ν
1	44	50.8	29.0	21.8	40.9	7.4	18%
2	53	41.3	28.8	12.5	34.6	3.4	10%
3	55	48.5	23.4	25.1	33.1	7.1	21%
4	62	36.6	22.7	13.9	29.2	2.6	9%
Overall		50.8	22.7	28.1	34.5	4.9	14%

Note: N_e is the number of emitters; Diff. is the difference between maximum and minimum; sd is the standard deviation; and ν is the coefficient of variation.

Conclusions

The high variation in emitter spacing indicates the need for improved quality control in manufacturing. In addition, the manufacturing process itself may need to be redesigned. In application, this variation means that crops should be planted after the system is installed to ensure correct corresponding crop spacing.

APPENDIX F. Time-lag Study

Introduction

It was supposed that at low pressures typical of IDEal drip systems the amount of time required for all emitters to begin flowing would have a significant effect on the overall uniformity. Thus, the effect of time-lag on emission uniformity was investigated.

Methodology

The test was performed using the same setup as described for the emitter performance tests using micro-tubes inserted to 5 cm. The lateral was clamped at the inlet to prevent any flow from entering the lateral. The supply tank was set to 1.005 m of head. The catch containers were then placed under each emitter. The clamp was then removed and the flow was started. The time for the last emitter to begin flowing was recorded, and the lateral inlet was again clamped shut. The lateral was allowed to drain, and the discharge volumes for each emitter were measured.

Results

Upon releasing the clamp from the lateral inlet, the inlet head varied from 1.005 to 0.995 m, thus for all practical purposes the inlet head was 1 m during the test. The time from the moment the clamp was released to the moment when the last emitter began flowing was 31 seconds. The time for the lateral to completely drain was 8.5 minutes; the time to drain is rather subjective; some emitters stop sooner than others.

The distribution of emitter discharge volumes along the lateral is shown in Fig. F.1. The maximum and minimum catch volumes were 94 and 33 ml, respectively, which

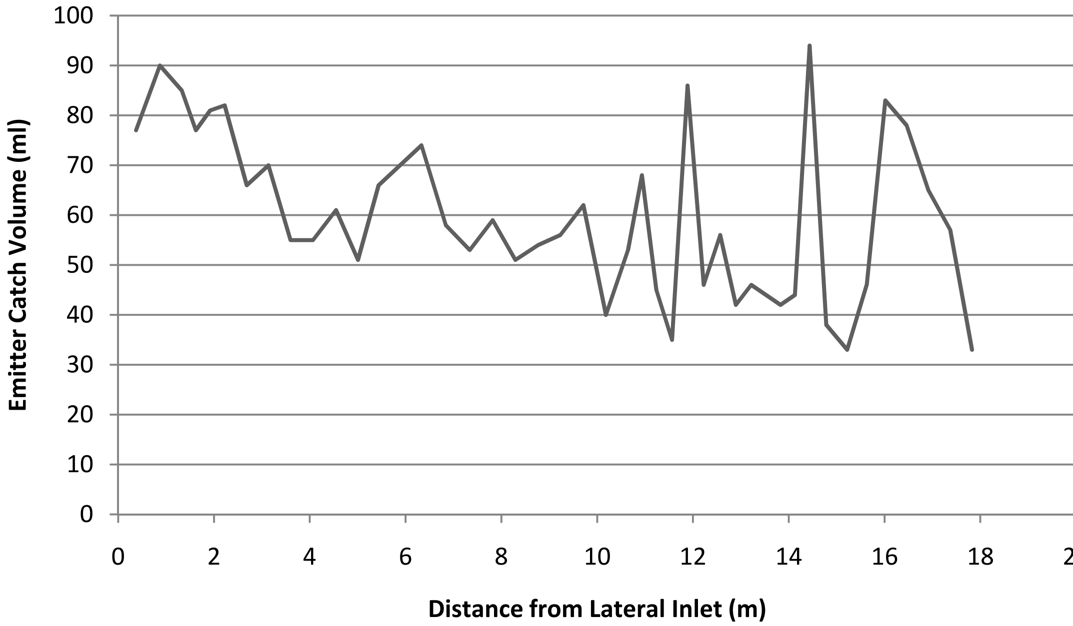

Fig. F.1. Effect of time-lag on emitter discharge volume distribution

yields a difference of 61 ml. The average catch volume was 60 ml, with a standard deviation of 16.6, and a coefficient of variation of 28%. While there was significant scatter in the results, there is a definite trend showing a decreasing catch volume along the length of the lateral. The scatter in the results can most likely be attributed to small variations in the elevations of the emitter outlets.

Conclusions

The difference between the maximum and minimum values appears quite large. However, when compared to the duration of a typical irrigation, a difference of 60 ml is a relatively small percentage of the overall application. In addition, lateral length in the field study area was generally much less than the tested 17.8 m. Thus the time-lag along one lateral has little effect on the uniformity along the lateral. However, the effect of time-lag on the emission uniformity along the lateral will be greater as the lateral length increases. In addition, this study does not address the effect of time-lag across several laterals in a system.

APPENDIX G. Field Study in the Central Rift Valley of Ethiopia

Introduction

Upon completion of laboratory testing, a selection of IDEal drip systems in the Central Rift Valley of Ethiopia was evaluated under actual field conditions. The objective of the study was to identify ways to improve the overall effectiveness of the systems. This was achieved by observing installation methods, and operation and maintenance practices, and by evaluating system performance. The results for each system analyzed are presented individually, following a daily field log format. A summary of evaluation results is then presented. Observations made during the installation of several systems are reported. Based upon the results of evaluations and observations, recommendations were made regarding all aspects of the system.

Evaluation Procedure

The objectives of the field study were accomplished by visiting IDEal drip systems that were already in use and by observing the installation of new systems. Farmers were interviewed and at select sites an evaluation of the system uniformity was performed. Field procedure was adapted from Merriam and Keller (1978) and the form found in Appendix L was used for data collection. Evaluations obtained information regarding: crops, water supply, operation and maintenance practices, system layout, and emission uniformity.

Location Information

The observers and date of observation were recorded. Each field was given a unique ID for easier reference. The coordinates of the field were obtained by the use of a global positioning system. The name of the farmer was also recorded.

Crops

The crop types, planting date, crop spacing (*Sp*), row spacing (*Sr*), and number of emitters per plant (*Np*) were recorded.

Soil

The approximate soil texture was recorded based on visual inspection and literature. The quality of soil preparation was evaluated as: Excellent: smooth, even soil preparation, with no/small clods less than 2 cm in diameter; Good: uneven field topography and/or clods of less than 2 cm in diameter; Fair: some clods of 2-5 cm in diameter; Poor: large clods greater than 5 cm in diameter.

Water Supply

Information regarding the water supply was recorded. The source (well, lined pond, unlined pond, etc.) and lift method (treadle pump, rope pump, etc.) were noted. The lift required, defined as the vertical distance from the lift method to the top of the storage tank was measured. The horizontal distance from the water source to the storage tank was also measured. The type and approximate volume of the storage container was recorded, as well as the time required to fill the tank. The minimum and maximum water levels, defined as the vertical distance from the sub-main to the tank outlet and inlet, respectively, were measured. Water supply handling was observed for ways in which water was filtered before entering the header tank. The pH of the supply water was measured using pH strips. The salinity of the irrigation water was measured using a salinity probe.

Irrigation

Farmers were interviewed to determine the frequency and duration of irrigation. Farmers were asked about the typical duration of the irrigation season and the amount of times the system was operated each season. In addition, they were asked if they irrigated the crop by any additional means. The system start-up time, defined as the time required for all emitters to begin flowing, was noted.

System

The history and characteristics of the drip system were determined through observations and interviews. The date the system was installed, who installed it, and how many seasons it had been used were recorded. The lengths of the mainline, submain, and laterals were measured. The approximate area of the field was calculated as the length of the submain times the length of the lateral. The filter was examined for cleanliness, and the farmer was asked how often and with what method they clean it. The number of valves in the system was recorded. The quality of the valve was analyzed for manufacturing debris, and cleanliness, and the stopcock-hole diameter was measured. The emitter type, insertion length, and emitter spacing were measured. The method of system storage during the off-season was noted. The farmer was asked about their feeling for the system, as well as any problems they may have with clogging, leaks, installation, maintenance, or operation. System operation practices were noted.

System Layout and Topography

A brief sketch was made of each system layout, indicating major topography of the irrigated area. Slopes were visually estimated and labeled on the diagram. Unless otherwise indicated in the results, the field slope was effectively zero at all locations evaluated.

Field Catchment

On a selection of systems, a field catchment was done to estimate the system uniformity. The field catchment was recorded using the table outlined by Merriam and Keller (1978) and is shown in Appendix L. Four laterals were analyzed. Where possible, the laterals were at the inlet, one third the length, two thirds the length, and the end of the submain. On each lateral, emitter flows were measured at two locations, A and B, at the inlet, one third the length, two thirds the length, and the end of the lateral. Thus, a total of 32 measurements were taken. Catch cups used were approximately 13 cm in diameter and 6 cm tall, with an approximate volume of 500 ml. Emitter loops were untied to ensure emitter discharge into the catch cup. The time for the header tank to completely drain was recorded, and the volumes from the catch cups measured. Volumes were measured using a set of graduated cylinders.

The average and standard deviation of all emitter flows was then calculated. The *CvU* was then calculated following Eq. (9). The performance criteria of *CvU* for low-cost drip irrigation systems serving small plots is: above 88% is excellent; from 88% to

80% is good; from 80% to 68% is acceptable; and less than 68% is unacceptable (Keller and Keller 2003).

Individual Evaluation Results and Discussion

October 20, 2008
Field ID: AG1
Farmer's Name: Bedhaso Tufa
Coordinates: N7° 58.709' E38° 41.237'
Location Description: Northeast of FTC in Abene Germama
Observed by: ET, Tolossa

The site information for field AG1 is presented in Table J.1. The farmer planted his crops before the rainy season began, and will continue to irrigate them until the pond from rain water harvesting is empty. In addition to using the drip system, the farmer also irrigates the crops by pumping water into the furrows (1hr/day) with the treadle pump. Minor leaks were observed in the supply hose. The farmer indicated that he likes the IDEal system much better than a Netafim system he also uses. This is because the emitters are easy to unclog in the IDEal system, which he does daily (see Fig. H.1). Field slope was about 1% downhill along the lateral length. Soil preparation was fair.

The system consisted of five laterals, with the main-submain connection being between the second and third laterals. Catchment was done on laterals one, two, four and five. During the catchment, several problems were noted. The second lateral was kinked at the lateral-submain connection. Thus, no flow entered the second lateral until after the kink was removed. It is speculated that the kink is a persisting problem. The submain at the second lateral position was tied to stake, which caused the submain to lift off the ground, consequently kinking the lateral. The farmer was unaware of the problem. In addition, there were three micro-tubes missing, which caused large leaks (see Fig. H.2).

Of the 32 emitter catchments, eight were effectively clogged, which corresponds to 25%. As a result, other emitters had very high flows. These high flows caused the catch cups to overflow, thus some volume was lost. The cups were consequently measured more than once to accommodate the large volume. Due to the large number of clogged emitters, it was difficult to estimate the system start-up time. During the testing, the farmer also continued to unplug the emitters that weren't working. Thus, leaks occurred wherever he was working.

The results from the field catchment are presented in Table I.1. The catchment was completed in 52 minutes. The average emitter flow, q_a, was 0.572 lph. This yielded a *CvU* of 40%, which is unacceptable. This is not unexpected, due to the problems noted above. Although the farmer says he is pleased with the system, the fact that he irrigates the same crops with surface irrigation suggests otherwise.

The system could benefit from:

- The availability of extra micro-tubes to replace those lost or permanently clogged.
- A better way to filter the water before it enters the header tank. While the cloth the farmer currently uses is a good idea, the cloth poor space is large (see Fig. H.3).
- An improved lateral-submain connection
- Routine maintenance by the farmer (unclogging the emitters)

October 23, 2008
Field ID: EC1
Farmer's Name: Halima Baneta
Coordinates: N8° 00.249' E38° 43.419'
Location Description: Elka Chelemo (North of Ziway, along main highway)
Observed by: ET, Tolossa

The site information for field EC1 is found in Table J.2. This is new drip system that was installed a little more than a week prior to the system evaluation. The farmer stated that she is pleased with the system so far. She feels that it saves her time and water.

The system is from a 20 m^2 kit. There are four laterals of 5 m each. About 1 m of material is unused at the end of each lateral because there is a fence that restricts the field size. The main and sub-main are both constructed of drip tape. There is an inline filter that is “cleaned daily,” however due to the condition of the filter prior to testing, this is doubtful (see Fig. H.4). The laterals are not staked down at each end, thus the laterals tend to expand and kink due to the heat/sunlight. However, the farmer stretches each lateral out prior to turning on the system. There are little to no clods on the soil, however some low spots in the field preparation cause some kinking in the lateral (see Fig. H.5).

The header tank is a 20 L bag that is filled by pumping water into a bucket, then carrying the bucket a distance of 10 m to the bag, which is 1.4 m above the ground. It takes approximate 10 minutes for this process to be accomplished. There is no process of filtering the water before it enters the bag, however the bag is emptied of dirt and debris periodically. There was significant kinking in the mainline connections (see Fig. H.6, A.7). There is one valve at the end of the mainline that is used to operate the system. The diameter of the hole through the stopcock was 6 mm. There was no manufacturing debris visible in the valve.

The field is irrigated twice every morning and evening, for a total of four times a day. The start-up time is 5 minutes. However, it should be noted that the first lateral on the sub-main begins operating almost immediately, after which the laterals begin filling in reverse order. This is reflected in the field catchment (see Table I.2). The irrigation duration is approximately 34 minutes. The irrigation season for this crop is approximately two months, which amounts to approximately 240 irrigations per season. After this crop is harvested, another irrigated crop will be planted in its place.

The field catchment yielded a q_a of 0.754 lph, with a *CvU* of 60.8%, which is unacceptable. Two of the 32 emitters measured were clogged in this system. The most noticeable problem was the difference in flow between laterals. One possible explanation for this is the lateral-submain connections. There is significant kinking at each junction in the submain (see Fig. H.8). In general, emitter flow rates are highest at the ends of each lateral. This could be due in part to the fact that the end of the field had a shallow (5-8 cm) depression, thus the emitters at the end of the lateral may be under greater pressure. However, this would mean that the additional 5-8 cm in elevation head is greater than the combined losses up to that point.

The system could benefit from:

- Regular cleaning of the inline filter
- A method of filtering the water before it enters the header tank
- A valve stopcock-hole diameter equal to the valve outlet inside diameter
- Improved lateral-submain connections
- Staking of the laterals
- Smoothing of the field micro-topography
- Unclogging the emitters

October 31, 2008
Field ID: FTC1
Farmer's Name:
Coordinates: N7° 57.847' E38° 43.211'
Location Description: Farmer Training Center North of Ziway. West half of the 200 m^2 kit.
Observed by: ET, Hailu, Saroj

A summary of the site information for FTC1 is found in Table J.3. The table is incomplete because a translator was unavailable for the farmer interview. However a field catchment and general measurements and observations were still carried out.

The system uses a 200 L barrel as the header tank, which is filled directly by using a rope and washer pump. There is no filter used before water enters the header tank. The tank takes approximately five minutes to fill. The minimum and maximum water levels are 1 and 1.8 m, respectively. There is a standard gate valve at the tank-mainline connection.

The system consists of 10-10 m laterals. The system serves a plot of onions with 6 plants per emitter. The mainline is 2.4 m long, and the submain is 7.9 m long. There is a filter in the mainline, which appeared clean. However, during operation there was significant leakage at the filter casing connection point. Since the system evaluated is part of a larger system, there is an inline valve at the beginning of the submain for operation. The valve stopcock-hole diameter was significantly smaller than the valve outlet inside diameter.

The soil preparation consisted of few clods and smooth topography. However the lateral was partially buried, possibly due to recent weeding/cultivation. Thus, many of the emitters were buried and the lateral had to be uncovered and emitters cleaned prior to operation (see Fig. H.9). One of the laterals was disconnected from the submain and had to be reattached (see Fig. H.10). It is unclear what caused the disconnection. It was very difficult to reattach the lateral due to the connection point being too tight. During the off-season, the system is taken off the field. However, the system is not stored in a methodical way, thus it must be untangled for reinstallation (see Fig. H.11).

The system start-up time was six minutes. The system catchment was done in 98 minutes. The catchment time does not represent the time for the entire tank to empty. The catchment was cut short due to time and weather constraints. However, when the system was turned off, less than 10 cm of hydraulic head remained in the tank. Thus it can be assumed that the catchment is a fairly accurate representation of an actual irrigation.

The catchment results for FTC1 are shown in Table I.3. The average emitter flow was 0.476 lph. The maximum and minimum flows were 1.111 and 0.141 lph, respectively. The system *CvU* was 69.8%, which is acceptable. Few completely clogged emitters were observed, although there were numerous emitters that appeared partially clogged. This could be due to the recent cultivating mentioned earlier. In addition, many of the emitters were angled down towards the soil, some of which were discharging directly into the soil. Several of the emitters were inserted in the wrong direction, with the micro-tube inlet pointing upstream. Other emitters were only inserted to 1 cm, and others had fallen out.

The system could benefit from:

- Correct insertion of the emitters
- A filter housing free of leaks
- More careful soil preparation/cultivation

- An improved lateral-submain connection
- A valve stopcock-hole diameter equal to the valve outlet inside diameter
- A method of filtering the water before it enters the header tank

November 5, 2008
Field ID: EC3
Farmer's Name: Geno Negeso
Coordinates: N8° 00.290' E38° 42.890'
Location Description: Elka Chelemo, North of Ziway. About 2 km west of main highway.
Observed by: ET, Tolossa

A summary of the site information for EC3 is found in Table J.4. Site EC3 is a recently installed 20 m^2 kit irrigating kale, with two plants per emitter. The soil preparation was good; almost no clods were observed, however there were some irregularities in the topography.

Water is carried to the header tank from a well approximately 125 m away. The header tank is a 20 L bag, which requires the volume of three water cans. It takes approximately 30 minutes to fill the bag. The well serves several houses in the village. Water is drawn from the well using a rope and bucket. The maximum water level of the header bag is 1.35 m. There is no method of filtering the water before it enters the bag; some debris was present.

The system consists of four laterals 5 m long each. The mainline passes through a control valve, and then enters an inline filter before it meets the submain. The inline filter is cleaned by the farmer as needed. The control valve stopcock-hole diameter was 5 mm. Some dirt and debris were observed in the stopcock (see Fig. H.12.). No major kinks were found in the lateral-submain connections.

One irrigation lasts approximately 40 minutes. The farmer irrigates twice per day (once in the morning and again in the evening). The laterals are not staked down, although stakes are in place. The farmer stretches each lateral out before turning on the water, as laterals kink as they expand due to sunlight (see Fig. H.13). In some cases plants and emitters were offset, meaning that emitters were found in-between plants.

The farmer reportedly unclogs emitters less than daily, or as needed. The emitter insertion length was 1-5 cm. One emitter was missing at the end of the lateral. This was easily fixed by kinking the end of the lateral above the final emitter hole. Two emitters were spaced at approximately 10 cm, perhaps as if the farmer had added an additional emitter as an afterthought (see Fig. H.14). There was a hole in the bottom of the lateral opposite the additional emitter, so there was no flow in the additional emitter. Some emitters were not tied in loops, such that the emitter outlet rested in the soil. Due to unseasonal and heavy rains, many of the emitters were clogged lightly by soil and debris that had splashed into the emitters. However, unclogging of these emitters was achieved simply by "flicking" the emitter with the finger.

The farmer said she is pleased with the system thus far because it saves her time and work. She expects it to increase her income because she would otherwise not use the land.

The field catchment results are found in Table I.4. The system start-up time was four minutes. The average emitter flow rate was 0.578 lph. The *CvU* was 83.8%, which is good. It should be noted that many of the emitters that were clogged due to rain were unclogged after the system had been running for quite some time. Thus it is possible that the *CvU* could be higher under normal conditions.

The system could benefit from:

- Extra emitters to replace those clogged or missing
- Stakes at lateral ends
- Correct emitter insertion length
- A method of filtering the water before it enters the header tank
- A valve stopcock-hole diameter equal to the valve outlet inside diameter

November 5, 2008
Field ID: EC4
Farmer's Name: Mekitu Bure
Coordinates: N7° 58.482' E38° 43.231'
Location Description: Elka Chelemo, North of Ziway. Along main highway.
Observed by: ET, Tolossa

A summary of site information for EC4 is presented in Table J.5. The assessment was done after a period of unseasonably heavy rains. Thus, the system had not been operated for several days. The 100 m^2 kit irrigates peppers that had been planted two weeks earlier. The field preparation was excellent, although it could be assumed that the heavy rains helped to smooth out any clods. The field slope was nearly zero in all directions.

The water supply is a well with a rope pump. The rope pump discharges directly into a 200 L barrel. The distance from the well to the tank is 5.8 m. It takes approximately 11 minutes to fill. The max and minimum water levels are 2 and 1.25 m, respectively. There is no method of filtering before the header tank.

The field is irrigated twice per day – once in the morning and again in the evening. The season length for the peppers is approximately 45 days. Thus, the system is operated about 90 times for this crop. The system was installed in May of 2008 and has been used to successfully irrigate three previous crops. During the rainy season the system is left on the field. It takes about one hour to complete one irrigation (to drain a full tank). System start-up time is six minutes.

The system mainline is six meters long. The mainline filter is cleaned before every irrigation. A tap connects the mainline to the header tank. The mainline connects to two submains of 3.7 m each. Each submain supplies 5 laterals of 10 m each. Some kinks were seen at the lateral-submain connections. This is most likely due to improper staking, which caused the submain to be curved (see Fig. H.15). When the submain is not straight, the lateral connections are crooked, causing the lateral to kink.

The emitter insertion length ranged from 1-10 cm. Many of the emitters were inserted in the wrong direction, with the end pointing upstream. Some emitter outlets were lying in the soil (see Fig. H.16). The farmer says she likes the system because it is easy to use. However, she said that in the rainy season everything becomes clogged. This was evident in the evaluation, as most emitters were slightly clogged due to the recent rains. However, when clogged from recent rains, the emitters can be fixed by simply "flicking" the end with the finger. The farmer soaks clogged emitters in a container of water (see Fig. H.17). The idea is that the water will soften the blockage, which can be "easily" removed later by blowing on one end of the emitter. Thus when she observes a clogged emitter, she simply replaces it with a "clean" one from the container of water.

The field catchment was done on the west section of submain. Thus, of the 5 laterals, laterals 1, 2, 4, and 5, were tested, which approximately corresponds to laterals at the inlet, 1/3 length, 2/3 length, and then end of the submain. It was assumed that both submains would have equal performance, neglecting emitter clogging, since the submains have equal length and number of laterals. As mentioned earlier, many emitters were partially clogged. However, during the catchment emitters were unclogged as rapidly as possible. Still, a number of emitters remained clogged throughout the duration of the evaluation.

The field catchment results are shown in Table I.5. The average emitter flow rate was 0.741 lph. The system *CvU* was 79.7%, which is acceptable, but nearly good.

The system could benefit from:

- Proper staking of the submain
- Unclogging the emitters
- Correct emitter insertion (direction, length, orientation)
- A method of filtering the water before it enters the header tank

November 12, 2008
Field ID: FTC2
Farmer's Name:
Coordinates: N7° 57.847' E38° 43.211'
Location Description: Farmer Training Center North of Ziway. East half of the 200 m^2 kit.
Observed by: ET, Holly, Lionel, Saroj

The field data for FTC2 is essentially identical to that of FTC1, thus it is included in Table J.3. The field has a small negative slope from the header tank in all directions; meaning that the emitter at the end of the lateral at the end of the submain is at the lowest elevation. Soil preparation was excellent. The system filter leaks around the filter casing.

Nearly all of the emitters were slightly clogged. They were easily unclogged during the field catchment by "flicking" the emitter outlets. Few of the emitters were observed to be seriously clogged – those that were appeared to have been clogged for quite some time because the onions around that emitter were long dead. The farmer was unavailable for interview, thus it is unclear how often the emitters are/need to be unclogged. The emitter insertion length ranged from 1-10 cm. Many of the emitters were inserted in the wrong direction, with the inlet pointing upstream. Several emitters were not tied in loops, thus the emitter outlet was lying in the soil.

The submain was not staked straight. At one location the lateral and submain were not touching the ground because the lateral was staked too tight (see Fig. H.18). Few kinks were observed at the lateral-submain connections. The lateral connection leaked at the 2/3 the submain length position.

The field catchment results are shown in Table I.6. The field catchment was collected in 57 minutes. System start-up time was two minutes. The average emitter flow rate was 0.724 lph. The system *CvU* was 79.1%, which is acceptable. Emitters were unclogged during the catchment, thus a second test may yield better uniformity. However, as mentioned earlier, the farmer's maintenance of the system is unknown. The small flow rate in the lateral at 2/3 the submain length could be attributed to emitter clogging, as well as a leak in the lateral-submain connection.

The system could benefit from:

- Regular system maintenance: unclogging of the emitters
- Proper lateral and submain staking
- Correct emitter insertion (length, direction, orientation)

- Improved lateral-submain connection
- Filter free of leaks
- Valve stopcock-hole diameter equal to the valve outlet inside diameter
- A method of filtering the water before it enters the header tank

November 13, 2008
Field ID: DH1
Farmer's Name:
Coordinates: N7° 38.405' E38° 40.673'
Location Description: Daka Horakalo. South of Ziway, near Lake Langano, East side of main highway
Observed by: ET, Tolossa, Getinet

The field lies on a bank next to a water harvesting pond. Recent heavy rains had caused the pond to overtop its banks, flooding the field. The system had not been operated since the water had receded, since the soil was still wet and the crops essentially ruined. A basic evaluation and maintenance on the system was performed.

The system was from a 20 m^2 kit. Apparently the farmer had installed it himself. The submains and laterals were not properly staked. Stakes were not placed in the corner of the connection tees and elbow.

The header tank was not placed such that the mainline had a straight connection to the submain (see Figs. H.19, H.20). Thus, kinks were found in the mainline at the inlet and outlet. In addition, the angle of the main-submain connection caused the submain to bend, kinking the first lateral. Submains were twisted between connections. The farmer complained that no water was entering the laterals. The filter was checked and found to be clogged. The farmer was taught how and when to clean the filter.

The soil preparation was poor. Significant undulations in the field micro-topography contributed to kinking in the lateral. The submain was raised above the field, which caused the first 40 cm of each lateral to be suspended above the ground. This caused the water from the emitter to run along the length of the lateral and drip at the location of the next emitter.

Emitter spacing was 40 cm. In the last lateral, emitter installation was incomplete and only about half the correct number of emitters had been inserted. Thus, holes were punched and emitters inserted for the remaining length of lateral. Many of the emitters were inserted in the wrong direction. Several of the emitter holes had been punched in the side of the lateral (see Fig. H.21). One emitter had been inserted on the bottom of the lateral. The emitter was removed, and the hole covered with tape.

Maintenance regarding the above issues was performed. The filter was cleaned, submains properly staked, and emitters fixed. The system was turned on to check for emitter clogging. No emitters were clogged. The system could further benefit from:

- Proper placement of the header bag
- Valve stopcock-hole diameter equal to the valve outlet inside diameter
- Lateral end stakes
- Smoothing of field micro-topography
- A method of filtering the water before it enters the header tank

November 17, 2008
Location ID: SDS
Coordinates: N9° 06.248’ E38° 59.139’
Location Description: Demonstration Site near Sendefa, east of Addis Ababa
Observed by: ET

Four recently installed drip systems were observed at the Sendefa Demonstration Site. Systems were not installed following the standard layout of the kits (ie. 100 m^2 or 20 m^2). Layouts for each system were specifically designed for the site. However, the systems were installed by field staff before they received the design. A field catchment was not performed.

Each system uses a bag suspended from a eucalyptus frame for the header tank (see Fig. H.22). Water is supplied to the header tank by lifting water from a storage pond using a treadle pump. Water is filtered before entering the header tank by using the filter cloth included in the drip kits. Staff indicated that the bags are easily blown around in the wind, possibly damaging the outer weaved plastic bag. To solve the problem, they always leave some water in the bag.

Water is siphoned from the bag to the system by inserting the mainline directly into the bag. A worker then disconnects the mainline from the filter and sucks the water out the mainline in order to start the siphon. In future irrigations the water can be started again by turning on the valve in the mainline. However this only works if the system was turned off before the water level dropped below the siphon inlet. In some cases the siphon inlet was inserted such that 20 cm or more of water was out of reach and unused.

Soil preparation was poor. Significant undulations in the field micro-topography caused numerous kinks. Many undulations were caused by the raised mounds surrounding the cabbage plants.

Submains were staked loosely at intermittent locations. This caused a very crooked submain (see Fig. H.23). This in turn caused the lateral-submain tees to be crooked, kinking the laterals. At one location three laterals were disconnected from the submain. The submain was then plugged at the disconnection using a stick and plastic (see Fig. H.24). Staff said that they did this because they didn't want to turn on the last three laterals. It was suggested they use an inline valve instead.

Lateral ends were not staked. The laterals lay loosely on the field, weaving around plants. Many emitters were inserted on the edge and/or bottom of the lateral (see Fig. H.25). Some were inserted with the inlet pointing upstream. Emitter insertion length was 1-15 cm. Some emitters were not tied in loops. In addition, many emitter outlets were in the soil.

The system could benefit from:

- Proper lateral and submain staking
- Proper emitter insertion (length, direction, orientation)
- Better soil preparation; smoothing of major undulations
- Inline valves in the mainline, and at other desired locations
- Regular maintenance (emitter unclogging)
- Siphon inserted to within 5 cm of bottom of the bag
- Valve stopcock-hole diameter equal to the valve outlet inside diameter
- A method of filtering the water before it enters the header tank

November 19, 2008
Field ID: AG2
Farmer's Name: Kufa Robel
Coordinates: N7° 58.958' E38° 41.419'
Location Description: Demonstration Site on farmer's property in Abene Germama.
Observed by: ET, Bruk

A summary of site information for field AG2 is found in Table J.6. The system evaluated was from a 20 m^2 kit. There is also a 200 m^2 kit installed at this location. The larger system was not evaluated because the system was not currently in operation due to a broken header tank tap. During a recent storm, strong winds blew the header tank off the stand, breaking the tap. According to field staff the tap cannot be replaced without taking the tap from another kit. Field staff plan to return to the site to insert the mainline directly into the barrel, sealing the connection with rubber.

The 20 m^2 kit irrigates both tomato and chickpea. The crops are spaced at 1 m, but are offset such that actual crop spacing relative to the system is 50 cm. Field staff said they instructed him not to plant more than one type of crop along the lateral, but he did otherwise. The farmer said that before installing the drip kits he had no previous experience with irrigation. The system had already been used to irrigate one crop of peppers. The farmer then moved the system by himself to a new location to irrigate the present crops. Soil preparation was good, with some clods and no large variations in micro-topography.

The water source is a lined storage pond. The pond had a new plastic cover to prevent evaporation; however the cover sunk after developing holes, and eventually tore completely away from the surface. A treadle pump is used to lift water a distance of 6 m to a 20 L header bag, which takes less than 2 minutes to fill. The max water level is 1.2 m, and the minimum is 0.75 m. There is no method of filtering the water before it enters the header tank.

The system consists of 4 laterals, each 6.1 m long. The emitter spacing is 30 cm. Many emitters were inserted in the wrong direction, and the insertion length was 1-15 cm. Several emitters were not tied in loops. The submain was twisted between the second and third laterals. The first lateral was slightly kinked at the submain connection. Small kinks were observed in the mainline inlet and outlet.

The farmer irrigates once a day, in the evening. He cleans the filter every three days, which he had cleaned the previous day. During the off-season he plans to roll the system up and place it in a box. He checks the emitters for clogging during every irrigation.

Two field catchments were done on the system. The first catchment was done before performing any changes to the system; the system was tested "as-is." The results of the first catchment are shown in Table 7. The field catchment was collected in 13 minutes (12 minutes for the tank to empty, and approximately one minute for the system to drain). The system startup time was about one minute; some water was observed in the system prior to start-up. The average emitter flow was 1.336 lph, and the system *CvU* was 75.7%, which is acceptable. About 3 emitters exhibited full clogging, while several others were partially clogged.

After obtaining the data in Table I.7, adjustments were made to the system. Every emitter was checked for insertion length, direction, and orientation. The insertion length was set to 5-10 cm, with the inlet pointing downstream. Emitters were tied in loops, with the outlets oriented in a positive angle. During the catchment the clogged emitters were identified and unclogged by "flicking." The kink at the inlet of the first lateral was removed. The twisted submain between the second and third lateral was corrected. The filter was cleaned of debris. The results of the catchment made after these adjustments are presented in Table I.8. The average emitter discharge for the adjusted system was 1.445 lph, which is an increase of 0.110 lph. The system *CvU* was good at 85.8%, an increase of 10.1 percentage points over the system before corrections. It is noted that one emitter in the catchment failed to discharge completely into the catch cup, thus it was omitted from the calculations.

After removing the kink in the first lateral inlet the emitter flow rate increased by 0.66 lph, or 5%. In addition, straightening the submain between the second and third laterals increased the emitter flow rate in the third and fourth laterals by an average of 0.202 lph (18%). While the variation in emitter discharge in the first two laterals actually increased slightly, the more dramatic decrease in variation in the third and fourth laterals was enough to improve in the uniformity of the system as a whole. It was noted that some of the emitters, particularly those that had been removed then reinserted in the correct direction, exhibited leakage around the emitter-lateral connection (see Fig. H.26). It may be that excessive reinsertion of the emitter stresses the hole in the lateral, causing a loose fit at the emitter-lateral connection.

November 24, 2008
Field ID: Golba4
Farmer's Name: Shek Aman Silo
Coordinates: N7° 50.449' E38° 43.405'
Location Description: Southeast of Adami Tullu, in the village of Golba.
Observed by: ET, Zerihun

A summary of site information for field Golba4 is found in Table J.7. The recently installed 20 m^2 kit irrigates four rows of kale, with two plants per emitter. The water supply is a bore hole with hand pump, 50 meters away. It takes approximately five minutes to fill the 20 L bag that serves as a header tank. There is no method of filtering the water before the header tank. Soil preparation was fair, however no kinking due to micro-topography was observed.

Prior to purchasing the system, the farmer had no experience with irrigation. The system is operated twice per day, once each morning and evening. The system has four laterals, averaging 5.9 m in length. The inline filter is cleaned once per week. There is one valve that operates the system, with a stopcock-hole diameter of approximately 6 mm.

The submain and laterals were staked relatively well; few kinks were observed. The final submain-lateral connection (elbow) was slightly crooked. Most emitters were inserted correctly. A few were inserted in the wrong direction, not tied in loops, and/or not inserted to the correct length. One emitter was purposely plugged with a thorn because the plants had died from cutworm. The farmer checks emitters for clogging during each irrigation.

A field catchment was performed without making any changes to the system; however, the filter was cleaned before operation. The results are shown in Table I.9. The catchment was collected in 13 minutes. The average emitter flow rate was 1.602 lph. The system *CvU* was 82.9%, which is good. No fully clogged emitters were observed.

After the catchment some adjustments were made to the system. Emitters were checked and set to the recommended insertion guidelines. Two lateral-submain connections were adjusted to remove kinking. The farmer was instructed on proper emitter insertion and cleaning. The system could further benefit from:

- Valve stopcock-hole diameter equal to the valve outlet inside diameter
- Better soil preparation

November 25, 2008
Field ID: AG3
Farmer's Name: Bati
Coordinates: N7° 57.831' E38° 41.458'
Location Description: Abene Germama, east of the FTC.
Observed by: ET, Dani

The 20 m^2 kit at AG3 was installed last season. The system was first used to irrigate peppers, but the crop was destroyed by birds. Kale was then planted in its place, but this crop was also destroyed by birds. When the rainy season came, the farmer gathered the system for storage in his house. While in storage the system was eaten by rats (see Fig. H.27). Only the header bag, micro-tubes, and various connectors and pieces of lateral remain. The farmer has no plans to replace the drip system. However, he recently purchased a treadle pump.

The farmer also owns a large spool of drip line (possibly Netafim), which was given to him by the Ethiopian Government. The government also provided him with a water storage pond, complete with cover. However, they did not supply him with any connectors for the drip line. Thus, he has not installed the system.

November 25, 2008
Field ID: AGFTC
Farmer's Name:
Coordinates: N7° 57.684' E38° 41.423'
Location Description: Farmer Training Center at Abene Germama
Observed by: ET, Dani

A summary of site information for field AGFTC is found in Table J.8. Observations made during the installation of the system are recorded below in the "Installation Observations" section. The farmer/manager was not available for interview, thus only basic measurements and a field catchment were performed.

The mainline feeds two submains of 4.4 m each. Each submain supplies 6 laterals. While there are inline valves for operation of each submain independently, it appears that the farmer irrigates both submains simultaneously. The valve stopcock-hole diameter was 5 mm for each valve. The filter was dirty, and the screen was torn at the bottom (see Fig. H.28).

Lateral-submain connections were good, with few kinks observed. This is contrary to the observations made during the installation. It is possible that after a month of laying in the sun the system had expanded a bit, relieving pressure on the lateral-submain connections, which were caused by laterals being staked very tightly.

Emitter insertion was good, with few micro-tubes inserted in the wrong direction and/or to the wrong length. Most emitters were angled downward, with the outlets in or near the soil. Some emitters were not tied in loops. Thus, some clogging of the emitter outlets was observed (see Fig. H.29).

The results of the field catchment are shown in Table I.10. The catchment was collected in 42 minutes, and the system start-up time was 2 minutes. The catchment was performed on one half of the system (laterals 1, 3, 4, and 6 tested on one submain). The average emitter flow rate was 0.701 lph. The system *CvU* was 87.3%, which is good. While some emitters were unclogged during the catchment, there was little major clogging observed. The relatively small variation between laterals suggests the lateral-submain connections are not restrictive. The system could be operated as two halves to increase the application. However the high uniformity suggests that having only 6 laterals on each submain, as opposed to 10, could be beneficial.

The system could further benefit from:

- Correct emitter orientation to prevent outlet clogging
- A method of filtering the water before it enters the header tank
- Valve stopcock-hole diameter equal to the valve outlet inside diameter
- New filter screen

Summary of Evaluation Results

A summary of the results for all field catchments is shown in Table G.1. The table is organized by the size of the kit installed. The area of the field (approximated as total submain length times lateral length), average volume applied per emitter (V_a), the irrigation duration, average emitter discharge, standard deviation of emitter discharges, system coefficient of variation uniformity, and the number of irrigations per day are presented.

For the 20 m^2 kits, the average volume applied per emitter was 345 ml. The average *CvU* was 78%. The maximum and minimum *CvU* was 85.8 and 60.8 %, respectively. While fields EC3 and EC1 required about the same time to irrigate, the *CvU* was quite different. The other 20 m^2 systems had an irrigation duration of 13 minutes, or about half that of EC3 and EC1. This may be due to filter clogging in EC3. The unacceptable *CvU* of EC1 was due to emitter clogging and kinks at the lateral-submain connections.

The 100 m^2 kit average application per emitter was 690 ml, and average *CvU* was 79%. Field AG1 was not included in the average calculations because it is doubtful the system is actually in use. Excluding AG1, the maximum and minimum *CvU* was 87.3 and 69.8%, respectively. Field AGFTC exhibited the highest *CvU*. This is probably due

Table G.1. Summary of Field Evaluations

Location ID	Area (m^2)	V_a (ml)	Duration (min)	q_a (lph)	sd (lph)	CvU (%)	Irrigations (per day)
20 m^2 kits							
EC3	16	347	36	0.578	0.094	83.8	2
EC1	16	427	34	0.754	0.296	60.8	4
Golba4	18	347	13	1.602	0.274	82.9	2
AG2							
Before	19	289	13	1.336	0.325	75.7	1
After	19	313	13	1.445	0.205	85.8	1
Average		**345**		**1.143**	**0.239**	**78**	
100 m^2 kits							
AG1	62	496	52	0.572	0.341	40.4	1
EC4	74	803	65	0.741	0.150	79.7	2
FTC1	79	778	98	0.476	0.144	69.8	
FTC2	79	688	57	0.724	0.151	79.1	
AGFTC	89	491	42	0.701	0.089	87.3	
Average*		**690**		**0.660**	**0.134**	**79**	

**Does not include field AG1*

to the absence of kinks at lateral-submain connections, few clogged emitters, correct emitter insertion, and equally distributed laterals between two submains.

The irrigation duration varied somewhat between 100 m^2 systems, and can most likely be attributed to emitter clogging and kinks in the lateral-submain connections. Unfortunately, evaluations for EC4 and FTC1 were performed after many days of heavy rain. This caused an unusually high number of clogged emitters, which were unclogged during the catchment by "flicking" with fingers.

The average application volume per emitter for 20 m^2 kits was half that of the 100 m^2 kits. Thus, to apply the same amount of water, the 20 m^2 kit should be operate twice as often. Based on the results of the evaluations, this is not occurring. The irrigation frequencies for the systems installed at the farmer training centers are unknown, but according to field staff the frequency is inconsistent due to poor system operation. How the farmers determine the irrigation frequency is unknown. However, the knowledge that the 20 m^2 kits apply half the water of the 100 m^2 kits per irrigation should help IDE staff determine the correct irrigation frequency.

Specific recommendations for improvement were provided for each system evaluated. Based on these recommendations and observations, general recommendations for all aspects of the system are given below in the "Recommendations" section. A summary of the coordinates of all systems installed, evaluated, and observed is presented in Table J.9.

In general emitters were unclogged by removing the emitter from the lateral and blowing through it to remove the obstruction. However, it may be that excessive reinsertion of the emitter stresses the hole in the lateral, causing a loose fit at the emitter-lateral connection, and thus leakage occurs. An easier and reliable way to unclog the emitter is by "flicking" the outlet with the finger (as described below in the "Recommendations" section). In cases where the emitters are extremely clogged, they can be removed and soaked in water to soften the obstruction.

System Installation

The installation process of several new drip systems was observed. Potential problems were identified, and suggestions were made to IDE field staff during installation for improvement. In this section, a general description of the installation process is given. The observations from individual sites are included in a daily-log format. General recommendations for the installation process are included below in the "Recommendations" section.

General Installation Methods

Installation methods generally follow the instructions included with the drip kit. Procedure varies somewhat depending on the size of the system (20 or 100 m^2). In the case of the 100 m^2 kit, the supply tank is placed on a stand of eucalyptus wood, usually about 1.5 m high. The mainline is then connected to the barrel, and the filter connected to the mainline. The mainline is usually connected to one end of the submain. In the 20 m^2 kits the mainline, submain, and laterals come preassembled. A bag that serves as a header tank is placed on a eucalyptus frame such that the bag outlet is about one meter above the ground.

Laterals are connected to the submain using the tee fittings provided in the kit. Each lateral-submain connection is staked down by placing a stake in one corner of the tee. Once all the laterals are connected, the water is turned on, and the air purged from each lateral. The lateral is plugged at the end by folding the end over at least twice and placing a small piece of lateral over the folded section. Once all laterals are filled, purged of air, and plugged, the lateral cross-section is "stretched out." This is done by pinching the lateral at the inlet with the thumb and forefinger. The hand is then run down the lateral about 50cm, thus applying more pressure to the lateral and effectively causing the lateral to more fully inflate (see Fig. H.30). After stretching, lateral ends are then staked down (see Fig. H.31). Holes are then punched in the lateral using the provided punching tool (see Fig. H.32). Holes are punched starting 10 cm from the lateral-submain connection. During the emitter insertion process, each person usually carries their own set of emitters, which they place in the dirt while punching the hole. Then the emitters are tied in a loop and inserted.

Installation Observations

October 15, 2008
Location ID: AGFTC
Coordinates: N7° 57.684’ E38° 41.423’
Location Description: The Farmer Training Center west of Ziway at Abene Germama.

The system installed was from a 100 m^2 kit. The system has 12 laterals, each 10 m long and spaced at 80 cm. The mainline connects to two submains that are equal in length. Each submain supplies 6 laterals, and is operated with an inline valve. The inline valve stopcock-hole diameter is much smaller than the valve outlet inside diameter. The system is supplied by a 200 L barrel that sits on a 1.5 m eucalyptus stand. The stand sits next to a 1 m high bank which surrounds a plastic lined pond, which serves as the water supply. Thus, it would have been easy to put the stand on the bank, giving an extra meter of hydraulic head. The barrel is filled by using a treadle pump to pump from the pond. The horizontal distance from pump to barrel is perhaps 4 m, however a hose of about 20 m is used because the farmers want to be able to use the hose for other purposes. The water is not filtered before entering the header tank. The barrel was rinsed by field staff before installing, and a mysterious white chemical was found inside.

The submain end stake was placed between the kink and double ring used to form the kink. This caused the submain to bend around the stake before passing through the double ring. This did not create a sufficient kink, and water leaked from the end of the submain. The problem was solved by sliding the double ring as close to the kink as possible, and placing the stake on the other side of the double ring.

Each lateral was staked at the inlet and end. However, laterals were staked so tightly that the submain was bent slightly between laterals. This contributed to kinks found in the lateral-submain connections. Laterals were not "stretched," neither was air purged from the system prior to emitter insertion.

Holes were then punched in the lateral using the supplied punching tool. Emitters were inserted at a length of 1-10 cm. Emitters were not oriented in any particular direction, thus some were pointing up, to the side, or angled down towards the soil.

October 31, 2008
Location ID: EC2
Coordinates: N8° 00.208' E38° 43.441'
Location Description: Elka Chelemo, North of Ziway, along main highway.

The system installed was from a 100 m^2 kit. Water is supplied by using a rope pump to fill a bucket, which is then carried about 5 m to the 200 L header tank. Water is filtered prior to entering the header tank. The system mainline was connected to the barrel by inserting the mainline directly into the barrel outlet spout (see Fig. H.33). The mainline supplies one submain, which feeds 11 laterals of approximately 10 m in length. There is no valve in the system. The filter casing leaked at the seal (see Fig. H.34).

Laterals were measured and cut during the middle of the previous day. When the installation was completed the following morning, it was found that several of the laterals were too short (see Fig. H.35). It is possible that this is because of the lateral expansion due to heat during cutting, or perhaps due to measurement error. The laterals were not "stretched" by IDE staff prior to purging the air from each lateral. Thus, the purpose and process of stretching the lateral was explained to them.

The soil preparation of the field was good; few significant clogs or topography undulations were observed. However a thorny plant was not removed and it punctured the lateral during installation.

No leaks were observed in the lateral-submain connections. It was observed that the laterals were staked nearly perpendicular to the submain. In addition, the lateral tension was such that the submain was not drastically bent. The lateral-submain connections were oriented at a zero degree angle on the horizontal plane, thus kinks at the connections were insignificant.

Emitters were inserted from 1-15 cm (see Figs. H.36, H.37). Some loops in the emitters were tied very tightly and near to one end. Some emitters were placed in the dirt prior to insertion, which may contribute to emitter clogging. There were not enough emitters included in the kit to finish the installation. IDE staff indicated that this happens quite frequently. However, it is unclear if this is due to packaging error, or if the amount included corresponds to 10 laterals with 30 cm emitter spacing. If the latter is the case, then installing a system with 11 laterals would be the cause of the lack of emitters.

November 6, 2008
Location ID: Golba1, Golba2, Golba3
Coordinates: N7° 50.342' E38° 43.455'; N7° 50.352' E38° 43.483'; N7° 50.209' E38° 43.302'
Location Description: Southeast of Adami Tullu, in the village of Golba

The installation of three 20 m^2 drip kits was observed in the village of Golba. The observations are presented for the three systems collectively, since the problems observed were common among all three systems.

In all three systems the laterals were not of equal length (see Fig. H.38). In one case the submain was twisted. Thus it was observed that during the installation it is necessary for the lateral-submain connections to be rotated in order for the submain to lay flat on the ground. In addition, laterals often come attached crooked and folded to the submain connections (see Figs. H.39, H.40). Thus, the laterals in many cases needed to be reattached to prevent kinking. However, because the lateral diameter is larger than the tee outside diameter the lateral must fold in order to "tightly" fit over the connection anyway.

The lateral-submain connection at the end of the submain (elbow) was kinked (see Fig. H.41). This is because the lateral was not staked perpendicularly to the submain. Kinks and leaks were observed at nearly all of the lateral-submain connections. In one case the submain was not in a straight line, causing kinks at all lateral connections. Inline valves had a stopcock-hole diameter much smaller than the valve outlet inside diameter.

Each of the header bags came from the factory with leaks. Visual inspection revealed several small holes near the bag outlet. To fix the problem IDE staff inserted a heavy plastic bag into the header bag to serve as a liner. The outlet was connected over the liner and the leak was essentially stopped.

Header bags were installed on an angle with reference to the submain. Thus, the mainline ran diagonally rather than perpendicularly to the submain. This caused kinks in the mainline at the inlet and outlet.

November 13, 2008
Location ID: ANFTC
Coordinates: N7° 21.718’ E38° 42.158’
Location Description: Farmer Training Center at Arsi Negele

The installation of a 200 m^2 kit was observed at the FTC on the east side of Arsi Negele. Due to time constraints, only the system layout was completed. FTC directors were then taught how to complete the emitter insertion and lateral staking.

Fourteen laterals of 13 m each were divided evenly between two submains. Lateral spacing was 80 cm. The system layout was created based on the available field area. However, it should be noted that only about 190 m of the indicated 220 m of lateral drip tape was included in the kit. Field staff indicated that this is common – drip kits do not contain the advertised length of drip tape.

Soil preparation was completed by first turning over the soil, then constructing beds and smoothing the soil. A 3-4-5 triangle geometry was used to ensure a right angle at the field corners.

It was observed that often times the submains are not connected securely to the tees. The submain should slide onto the tee as far as possible, otherwise the connection will come apart when the submain is stretched and staked. The mainline-tank tap connection point leaked (see Fig. H.42). This was fixed by wrapping the connection with black electrical tape.

A treadle pump was used to lift water from a water harvesting pond a horizontal distance of about 15 m, not including suction. The hose used was about 10 m longer than necessary. It was recommended they cut the hose to the proper length, however staff chose to leave the hose as it was for the time being. The included filter cloth was used to filter the water entering the tank (see Fig. H.43). A significant amount of large debris was captured by the filter. Suspended debris was observed in the pond because of recent heavy rains. It is supposed that over time the larger debris will settle to the bottom of the pond.

Purging of the air from laterals and lateral cross-section stretching were not performed by field staff. Thus, the process was again demonstrated and the purpose explained. It is supposed that the field staff either doubt or do not understand the importance of the technique, as this has been a common occurrence throughout the field observations.

Two inline control valves were installed to enable alternation of irrigation sets. The valve stopcock-hole diameter was smaller than the valve outlet inside diameter. The small hole in one of the valves was carved out using a knife. However, this left significant debris in the stopcock.

Summary of Observations

Six drip system installations were observed. A summary of the coordinates of all systems installed, evaluated, and observed is presented in Table J.9. Detailed recommendations regarding the installation process are included below in the "Recommendations" section.

In half of the installations lateral cross-sections were not stretched using the procedure outlined in the "General Installation Methods" section. In all cases IDE staff had to be reminded/taught the procedure. It is supposed that the field staff either doubt or do not understand the importance of the technique, as this was a common problem throughout the field observations.

In general, the emitter insertion process is not as efficient or accurate as it could be. Each person punching holes in the lateral also carries a number of emitters which are placed in the dirt prior to insertion. This process is time consuming, and also presents an opportunity for particles to enter the emitter and/or lateral during insertion. In addition, more emphasis was given to field staff and farmers that the insertion length be 5-10 cm, with the outlet oriented upward and away from the soil.

IDE staff indicated that in many cases there are not enough emitters included in the kit to finish the installation. According to field staff, 20 m^2 kits come with only 50 emitters, but they should come with at least 60 (four 5 m laterals, at 30 cm emitter spacing). In larger kits, the problem may be due to the fact that the advertised length of drip tape is not included, which is a common problem according to field staff. This is most likely due to poor manufacturing of the drip tape. Because the drip tape is sold by weight, if the wall thickness is greater than advertised the roll will have less than the advertised length. The number of emitters included in the kit should equal the total length of drip tape times the minimum emitter spacing.

In both the installations and the evaluations the inline control valves had a stopcock-hole diameter much smaller than the valve outlet inside diameter (see Appendix K). This will undoubtedly cause too much head loss. The small hole in one of the valves was carved out using a knife. However, this left significant debris in the stopcock.

In several cases, the header tank (barrel) was rinsed by field staff before installing. Cleaning always revealed the presence of a mysterious chemical. The chemical may be toxic to health and the environment. Barrels should be cleaned by the supplier.

Improper staking of the laterals and submains leads to kinks at the lateral-submain connector tees. While the current connector is not efficient because of the kinking and leaking outlined in the observations, when staked at right angles it can perform acceptably.

Kinking in the mainline of 20 m^2 kits is common. This is most likely caused by incorrect placement of the header bags. If the mainline is placed on an angle with respect to the submain it will kink at the inlet and outlet.

Recommendations

Based upon the results of the installations, evaluations, and observations included in the previous sections, recommendations for improvement for IDEal drip systems were identified. Recommendations address system manufacturing, installation, and operation and maintenance. Unless otherwise stated, recommendations apply to systems of all sizes.

Manufacturing

- All parts of the drip kit should come branded so that people know that the system comes from IDE.
- Header tank (barrel) should be cleaned by the manufacturer/supplier before being supplied to the farmer. Previously used barrels sometimes contain unknown chemicals that may be toxic.

- The inline valve stopcock-hole diameter should be equal to the valve outlet inside diameter to reduce the head loss in the valve (see Appendix K). This will also reduce the tendency of the valve to clog with debris.
- Lateral rolls should come with manufacturing information.
- Lateral manufacturing/packaging must be improved so that the advertised length of lateral drip tape is included in the kit.
- A sufficient number of micro-tubes should be included in the kit. The number of emitters should equal the total length of drip tape included in the kit times the minimum emitter spacing (30 cm).
    - Additional micro-tubes (perhaps 10) could be provided to replace those that are permanently clogged or lost.
- Larger submain-lateral connection tee (tee OD ≈ lateral ID). This will reduce the tendency for leaks to occur at the tee, and eliminate the lateral folding/kinking at the tee.
- Readily available extra system components to replace those lost, broken, etc. This means that farmers need to have available to them the option of buying the system as a complete kit, and also individual system components.
- A 50 m^2 kit (or whatever IDE determines is the smallest kit size that is prosperous for the farmer) should be made available. More farmers purchase the 20 m^2 kits simply because it is the cheapest, and thus represents the smallest risk. However it is doubtful the 20 m^2 kit increases the farmer's income enough to enable them to expand the system.
- For 20 m^2 kits:

- Kits should not come preassembled. This will allow the farmer to customize the system to his field (i.e. lateral length, row spacing). In addition, it will eliminate the problem of the unequally precut laterals. Preassembly saves little installation time because the submains and laterals have to be reattached to the connections anyway to reduce folding, twisting, and/or kinking.
- Better quality control for header bags to eliminate leakage.
- Mainline should not be made of drip tape. It kinks too easily if the header bag is not installed precisely (as recommended below). Even when installed precisely, kinks may form at the mainline connections anyway because the fittings are too small.

- In 100 and 200 m^2 kits:
    - A rubber gasket or improved filter manufacturing to prevent leakage in filter casing.
    - The mainline and submain diameter should be at least equal, if not greater than, the diameter of the laterals. This will reduce head loss due to friction in the main and submain. The larger main and submain will allow for a larger submain-lateral connection tee (as discussed above).

Installation

The following items are recommended to improve the system installation process. These should be reviewed and discussed by IDE field staff. Where applicable, the items should be taught to farmers and suppliers by IDE field staff.

Purchasing

- As recommended earlier in the "Manufacturing" section, availability of extra system components to replace those lost, broken, etc is a must. Currently IDE staff must "rob" another kit in order to replace broken parts. In addition, most farmers seem unaware that replacement of broken parts is an option, thus when something breaks the system is abandoned.
- The farmer needs to pick up the kit in person. IDE staff should not hand-deliver the kit. This will help farmers see where they can find extra parts, kits, other technologies, etc.

Soil Preparation

- Remove all thorny plants and weeds before laying out the system.
- Field should be smooth and free of major or sudden undulations (see Fig. H.44). This will allow for a more normal pressure distribution as well as prevent kinks due to micro-topography.
- Soil should be free of clods that will produce major variations in micro-topography or that could obstruct emitter flow.

Water Supply

- It should be explained to the farmer that the filter cloth included with the kit is to be used at all times to filter the water before entering the header tank.
- For locations using a treadle pump, the hose that feeds the header tank should be as short as possible/practical to allow for easier pumping.

- For fields with small slope (less than 3-4%) the header tank should be placed at the highest practical elevation on the field, with submains and/or laterals running downhill.
- For 20 m^2 kits:
  - Header bag should be placed parallel to the submain. The mainline should be parallel to the laterals. This will prevent kinks from forming in the mainline connections.
  - The mainline should be tight (i.e. not sagging). If the header bag is placed too close to the submain, the mainline will be too long and kinks will form due to sagging.
- For 100 and 200 m^2 kits
  - Where possible, the header tank should be placed at the head of the field and in the middle, such that two equal submains can attach to the mainline. This will allow the system to be operated as two independent halves by installing inline control valves on either side of the mainline-submain connection.

Main, Submain, and Laterals

- Where possible, the mainline should feed two submains (as described above).
- The current stock of inline control valves should be drilled out such that the stopcock-hole diameter is equal to the valve outlet inside diameter.
- Submain should be staked in a straight line, with no bends or angles.

- The submain should slide onto the tee as far as possible, otherwise the connection will come apart when the submain is stretched and staked.
- Laterals should be staked perpendicularly (right angle) to the submain. This will prevent kinks at the submain connection.
- The lateral part of the lateral-submain connector tee should be horizontal. If it is angled up or down it will cause kinks at the connection.
- Lateral cross-sections should be stretched after the system has filled with water, and been purged of air, and before lateral staking, using the process described in the "General Installation Methods" section.
- For 20 m^2 kits:
    - Submain should lay flat, with no twists. This is accomplished by rotating the submain at the lateral-submain connections.

Emitter Insertion

- Emitter insertion should be done in pairs: two people per lateral. One person ties and hands the emitter to the person punching the holes, who then inserts the emitter into the lateral. This speeds up the insertion process, and also keeps the emitters clean because they are not placed in the soil prior to insertion.
- Emitters should be oriented with the outlet pointing up. In the case where there is only one emitter per plant, the emitter may be angled toward the plant. However the outlet should always point up, rather than down, to keep the outlet out of the soil to prevent clogging.

- Emitters should be inserted with the inlet pointing downstream, to a distance of 5-10 cm. If less than this the emitter may fall out, or cause the emitter outlet to be at an unnecessarily high elevation. Inserting to greater than 10 cm may increase the head loss associated with each emitter.
- A loop should be loosely tied near the middle of the emitter, such that 5-10 cm of emitter remains for insertion. Doing otherwise may contribute to emitters being inserted outside the recommended range.

Operation and Maintenance

- Farmers should be instructed on the correct irrigation frequency. (20 m^2 kits require twice the number of irrigations as the 100 m^2 kits.)
- Water should be filtered before entering the header tank using the included filter cloth.
- The inline filter should be checked, and cleaned if necessary, before each irrigation. Guidelines on how and when to clean the filter should be given to the farmer.
- Emitters should be checked for clogging during each irrigation.
    - Unclogging should be attempted first by "flicking" the end of the emitter. This is accomplished by hitting the outlet of the emitter with the end of the finger. This method is particularly successful when the emitter has become clogged from lying in the dirt or from precipitates in the water collecting in the outlet.

    - If this method does not work, the emitter should be replaced with a clean emitter. If possible, the clogged emitter should then be soaked in a bucket of water for a few hours, or as long as necessary. After soaking, the emitter is unplugged by placing one end of the emitter in the mouth and blowing through the emitter to remove the clog, which should have been softened from the soaking.
    - Excessive removal/reinsertion of the micro-tube stresses the hole in the lateral, causing a loose fit, and thus leaks, at the emitter-lateral connection.
    - For details on emitter insertion guidelines, see above.
- Replace broken and/or lost components as necessary.
- Methods of system storage during the off-season need to be investigated. Farmers have indicated that everything becomes clogged when not in use during the rainy season, suggesting the system should be stored. However it is unclear whether or not the farmers are currently capable of correctly reinstalling the system afterwards. In addition, an organized method for storage needs to be outlined in order to prevent damage to the system during storing. If stored, the farmer must ensure that the system is protected from damage (i.e. rats).

APPENDIX H. Photographs of the Field Evaluations in Ethiopia

Fig. H.1. Farmer at AG1 cleaning a clogged emitter

Fig. H.2. Missing emitter. AG1.

Fig. H.3. Filtering by placing a cloth over the supply hose outlet. AG1

Fig. H.4. Clogged inline filter. EC1

Fig. H.5. Kink in the lateral due to micro-topography. EC1.

Fig. H.6. Kink in the mainline at the connection with the head tank. EC1.

Fig. H.7. Kink in the mainline at the connection with the valve. EC1.

Fig. H.8. Kink in the lateral at the connection with the submain. EC1.

Fig. H.9. Buried lateral and micro-tube. FTC1

Fig. H.10. Lateral-submain disconnection. FTC1.

Fig. H.11. Off-season storage. FTC1.

Fig. H.12. Debris in the valve stopcock. EC3.

Fig. H.13. Kink in lateral from expansion due to heat/sunlight. EC3.

Fig. H.14. Additional emitter spaced at 10 cm. EC3.

Fig. H.15. Improper submain staking. This causes a curved submain, which kinks the lateral. EC4.

Fig. H.16. Emitter outlet lying in the soil. EC4.

Fig. H.17. Emitter soaking to remove clogs. EC4.

Fig. H.18. Lateral and submain tension. This caused the lateral to be elevated above ground. FTC2.

Fig. H.19. Improperly placed header bag for 20 m^2 kit. DH1.

Fig. H.20. Improper placement of the header bag. This causes kinks in the laterals and mainline DH1.

Fig. H.21. Incorrect emitter insertion. The emitter inlet points upstream, and the hole is punched off-center. DH1.

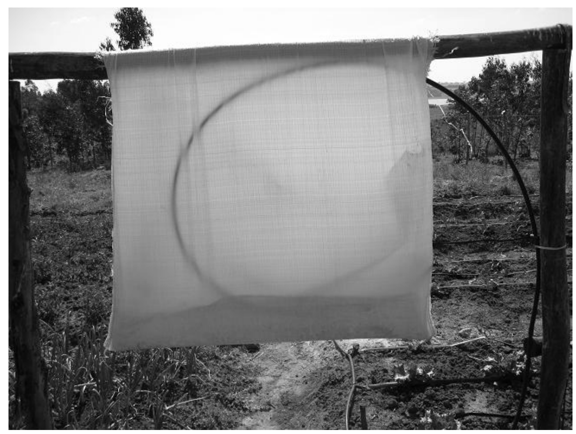

Fig. H.22. Header bag with siphon. SDS.

Fig. H.23. Poorly staked submain. SDS.

Fig. H.24. Disconnected submain. The free end is plugged with a stick and plastic. SDS.

Fig. H.25. Emitter inserted into the edge of a twisted lateral. SDS.

Fig. H.26. Leak at the emitter-lateral connection. AG2.

Fig. H.27. Drip system eaten by rats while in storage. AG3.

Fig. H.28. Tear in the filter screen. AGFTC.

Fig. H.29. Emitter outlet clogged from discharging into soil. AGFTC.

Fig. H.30. Stretching the lateral cross-section by increasing the pressure

Fig. H.31. Lateral end stake

Fig. H.32. Punching holes in the lateral for emitter insertion

Fig. H.33. Mainline inserted directly into the header tank outlet spout. EC2.

Fig. H.34. Leak in the filter casing. EC2.

Fig. H.35. Unequal lateral lengths. EC2.

Fig. H.36. Emitter inserted to less than 1 cm. EC2.

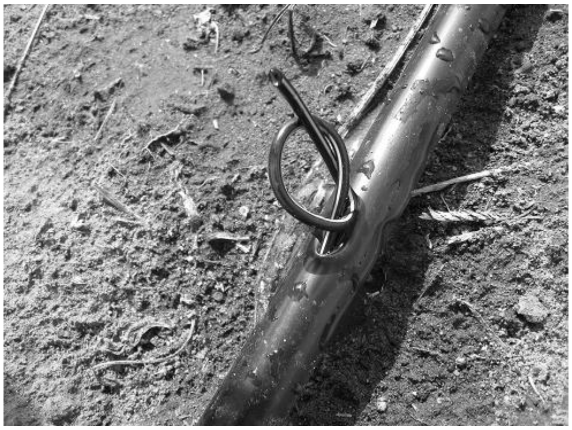

Fig. H.37. Emitter inserted to greater than 10 cm. EC2.

Fig. H.38. Uneven lateral length. Golba2.

Fig. H.39. Lateral attached crooked and folded. Golba3.

Fig. H.40. Lateral folded at submain tee. Golba1.

Fig. H.41. Lateral at end of submain kinked due to improper staking. Golba2.

Fig. H.42. Leak at the mainline-tank tap connection. ANFTC.

Fig. H.43. Debris filtered from the water before entering the header tank. ANFTC.

Fig. H.44. Excellent soil preparation. No clods or major variations in micro-topography.

APPENDIX I. Individual Field Catchment Results from Selected Sites in Ethiopia

Table I.1. Field Catchment Results for AG1

Emitter Location on the Lateral		**Lateral Location on the Submain**							
		Lateral #1		**Lateral #2**		**Lateral #4**		**Lateral #5**	
		ml	**lph**	**ml**	**lph**	**ml**	**lph**	**ml**	**lph**
Inlet	**A**	1015	1.171	925	1.067	775	0.894	810	0.935
	B	925	1.067	795	0.917	760	0.877	790	0.912
	Avg.		**1.119**		**0.992**		**0.886**		**0.923**
1/3 L	**A**	0	0.000	0	0.000	90	0.104	535	0.617
	B	1270	1.465	0	0.000	250	0.288	535	0.617
	Avg.		**0.733**		**0.000**		**0.196**		**0.617**
2/3 L	**A**	660	0.762	0	0.000	530	0.612	800	0.923
	B	725	0.837	505	0.583	440	0.508	230	0.265
	Avg.		**0.799**		**0.291**		**0.560**		**0.594**
End	**A**	0	0.000	0	0.000	0	0.000	15	0.017
	B	750	0.865	55	0.063	475	0.548	1197	1.381
	Avg.		**0.433**		**0.032**		**0.274**		**0.699**
Average/Lateral:			**0.771**		**0.329**		**0.479**		**0.708**

Table I.2. Field Catchment Results for EC1

Emitter Location on the Lateral		**Lateral Location on the Sub-Main**							
		Inlet		**1/3 L**		**2/3 L**		**End**	
		ml	**lph**	**ml**	**lph**	**ml**	**lph**	**ml**	**lph**
Inlet	**A**	605	1.068	297	0.524	390	0.688	255	0.450
	B	550	0.971	280	0.494	255	0.450	370	0.653
	Avg.		**1.019**		**0.509**		**0.569**		**0.551**
1/3 L	**A**	565	0.997	330	0.582	370	0.653	335	0.591
	B	650	1.147	290	0.512	385	0.679	0	0.000
	Avg.		**1.072**		**0.547**		**0.666**		**0.296**
2/3 L	**A**	565	0.997	300	0.529	10	0.018	460	0.812
	B	640	1.129	290	0.512	370	0.653	465	0.821
	Avg.		**1.063**		**0.521**		**0.335**		**0.816**
End	**A**	755	1.332	460	0.812	635	1.121	575	1.015
	B	730	1.288	530	0.935	370	0.653	585	1.032
	Avg.		**1.310**		**0.874**		**0.887**		**1.024**
Average/Lateral:			**1.116**		**0.613**		**0.614**		**0.672**

Table I.3. Field Catchment Results for FTC1

Emitter Location on the Lateral		Lateral Location on the Sub-Main							
		Inlet		1/3 L		2/3 L		End	
		ml	lph	ml	lph	ml	lph	ml	lph
Inlet	A	800	0.490	380	0.233	330	0.202	685	0.419
	B	845	0.517	665	0.407	635	0.389	600	0.367
	Avg.		**0.504**		**0.320**		**0.295**		**0.393**
1/3 L	A	930	0.569	850	0.520	655	0.401	490	0.300
	B	980	0.600	770	0.471	230	0.141	650	0.398
	Avg.		**0.585**		**0.496**		**0.271**		**0.349**
2/3 L	A	735	0.450	690	0.422	575	0.352	705	0.432
	B	1815	1.111	1195	0.732	680	0.416	1260	0.771
	Avg.		**0.781**		**0.577**		**0.384**		**0.602**
End	A	860	0.527	905	0.554	680	0.416	760	0.465
	B	865	0.530	1295	0.793	625	0.383	745	0.456
	Avg.		**0.528**		**0.673**		**0.399**		**0.461**
Average/Lateral:			**0.599**		**0.517**		**0.338**		**0.451**

Table I.4. Field Catchment Results for EC3

Emitter Location on the Lateral		Lateral Location on the Sub-Main							
		Inlet		1/3 L		2/3 L		End	
		ml	lph	ml	lph	ml	lph	ml	lph
Inlet	A	430	0.717	335	0.558	280	0.467	140	0.233
	B	470	0.783	405	0.675	355	0.592	430	0.717
	Avg.		**0.750**		**0.617**		**0.529**		**0.475**
1/3 L	A	380	0.633	265	0.442	405	0.675	330	0.550
	B	270	0.450	265	0.442	295	0.492	270	0.450
	Avg.		**0.542**		**0.442**		**0.583**		**0.500**
2/3 L	A	300	0.500	365	0.608	375	0.625	390	0.650
	B	370	0.617	460	0.767	305	0.508	420	0.700
	Avg.		**0.558**		**0.688**		**0.567**		**0.675**
End	A	470	0.783	400	0.667	295	0.492	250	0.417
	B	405	0.675	335	0.558	290	0.483	340	0.567
	Avg.		**0.729**		**0.613**		**0.488**		**0.492**
Average/Lateral:			**0.645**		**0.590**		**0.542**		**0.535**

Table I.5. Field Catchment Results for EC4

Emitter Location on the Lateral		Lateral Location on the Sub-Main							
		Inlet		1/3 L		2/3 L		End	
		ml	lph	ml	lph	ml	lph	ml	lph
Inlet	A	955	0.882	555	0.512	955	0.882	1035	0.955
	B	1290	1.191	1015	0.937	910	0.840	950	0.877
	Avg.		**1.036**		**0.725**		**0.861**		**0.916**
1/3 L	A	670	0.618	570	0.526	700	0.646	625	0.577
	B	680	0.628	715	0.660	435	0.402	695	0.642
	Avg.		**0.623**		**0.593**		**0.524**		**0.609**
2/3 L	A	900	0.831	820	0.757	950	0.877	1080	0.997
	B	865	0.798	230	0.212	770	0.711	855	0.789
	Avg.		**0.815**		**0.485**		**0.794**		**0.893**
End	A	845	0.780	805	0.743	915	0.845	900	0.831
	B	625	0.577	880	0.812	820	0.757	665	0.614
	Avg.		**0.678**		**0.778**		**0.801**		**0.722**
Average/Lateral:			**0.788**		**0.645**		**0.745**		**0.785**

Table I.6. Field Catchment Results for FTC2

Emitter Location on the Lateral		Lateral Location on the Sub-Main							
		Inlet		1/3 L		2/3 L		End	
		ml	lph	ml	lph	ml	lph	ml	lph
Inlet	A	670	0.705	578	0.608	744	0.783	715	0.753
	B	750	0.789	750	0.789	400	0.421	775	0.816
	Avg.		**0.747**		**0.699**		**0.602**		**0.784**
1/3 L	A	635	0.668	730	0.768	625	0.658	615	0.647
	B	1120	1.179	750	0.789	500	0.526	590	0.621
	Avg.		**0.924**		**0.779**		**0.592**		**0.634**
2/3 L	A	860	0.905	590	0.621	295	0.311	640	0.674
	B	755	0.795	555	0.584	490	0.516	570	0.600
	Avg.		**0.850**		**0.603**		**0.413**		**0.637**
End	A	880	0.926	950	1.000	280	0.295	775	0.816
	B	930	0.979	905	0.953	960	1.011	620	0.653
	Avg.		**0.953**		**0.976**		**0.653**		**0.734**
Average/Lateral:			**0.868**		**0.764**		**0.565**		**0.697**

Table I.7. Field Catchment Results for AG2 Before Adjustments

Emitter Location on the Lateral		Lateral Location on the Sub-Main							
		Inlet		1/3 L		2/3 L		End	
		ml	lph	ml	lph	ml	lph	ml	lph
Inlet	A	280	1.292	350	1.615	385	1.777	5	0.023
	B	355	1.638	320	1.477	320	1.477	265	1.223
	Avg.		**1.465**		**1.546**		**1.627**		**0.623**
1/3 L	A	295	1.362	360	1.662	385	1.777	275	1.269
	B	320	1.477	365	1.685	230	1.062	300	1.385
	Avg.		**1.419**		**1.673**		**1.419**		**1.327**
2/3 L	A	340	1.569	370	1.708	110	0.508	225	1.038
	B	330	1.523	350	1.615	215	0.992	275	1.269
	Avg.		**1.546**		**1.662**		**0.750**		**1.154**
End	A	335	1.546	300	1.385	225	1.038	210	0.969
	B	300	1.385	400	1.846	215	0.992	250	1.154
	Avg.		**1.465**		**1.615**		**1.015**		**1.062**
Average/Lateral:			**1.474**		**1.624**		**1.203**		**1.041**

Table I.8. Field Catchment Results for AG2 After Adjustments

Emitter Location on the Lateral		Lateral Location on the Sub-Main							
		Inlet		1/3 L		2/3 L		End	
		ml	lph	ml	lph	ml	lph	ml	lph
Inlet	A	355	1.638	315	1.454	395	1.823	110	0.508
	B	360	1.662	330	1.523	355	1.638	305	1.408
	Avg.		**1.650**		**1.488**		**1.731**		**0.958**
1/3 L	A	325	1.500	320	1.477	400	1.846	275	1.269
	B	335	1.546	315	1.454	260	1.200	320	1.477
	Avg.		**1.523**		**1.465**		**1.523**		**1.373**
2/3 L	A	320	1.477	385	1.777	200	0.923	285	1.315
	B	340	1.569	355	1.638	310	1.431	275	1.269
	Avg.		**1.523**		**1.708**		**1.177**		**1.292**
End	A	325	1.500	320	1.477	305	1.408	155*	0.715*
	B	310	1.431	420	1.938	305	1.408	290	1.338
	Avg.		**1.465**		**1.708**		**1.408**		**1.338**
Average/Lateral:			**1.540**		**1.592**		**1.460**		**1.188**

**Spillage; not included in calculations*

Table I.9. Field Catchment Results for Golba4

Emitter Location on the Lateral		Lateral Location on the Sub-Main							
		Inlet		1/3 L		2/3 L		End	
		ml	lph	ml	lph	ml	lph	ml	lph
Inlet	A	395	1.823	330	1.523	290	1.338	265	1.223
	B	410	1.892	395	1.823	375	1.731	300	1.385
	Avg.		**1.858**		**1.673**		**1.535**		**1.304**
1/3 L	A	485	2.238	395	1.823	330	1.523	315	1.454
	B	350	1.615	370	1.708	360	1.662	350	1.615
	Avg.		**1.927**		**1.765**		**1.592**		**1.535**
2/3 L	A	340	1.569	380	1.754	160	0.738	270	1.246
	B	350	1.615	365	1.685	285	1.315	220	1.015
	Avg.		**1.592**		**1.719**		**1.027**		**1.131**
End	A	385	1.777	340	1.569	310	1.431	380	1.754
	B	490	2.262	315	1.454	370	1.708	435	2.008
	Avg.		**2.019**		**1.512**		**1.569**		**1.881**
Average/Lateral:			**1.849**		**1.667**		**1.431**		**1.463**

Table I.10. Field Catchment Results for AGFTC

Emitter Location on the Lateral		Lateral Location on the Sub-Main							
		Inlet		1/3 L		2/3 L		End	
		ml	lph	ml	lph	ml	lph	ml	lph
Inlet	A	550	0.786	555	0.793	615	0.879	450	0.643
	B	540	0.771	545	0.779	495	0.707	465	0.664
	Avg.		**0.779**		**0.786**		**0.793**		**0.654**
1/3 L	A	530	0.757	455	0.650	505	0.721	380	0.543
	B	500	0.714	425	0.607	420	0.600	395	0.564
	Avg.		**0.736**		**0.629**		**0.661**		**0.554**
2/3 L	A	640	0.914	560	0.800	505	0.721	460	0.657
	B	555	0.793	505	0.721	415	0.593	510	0.729
	Avg.		**0.854**		**0.761**		**0.657**		**0.693**
End	A	435	0.621	420	0.600	535	0.764	385	0.550
	B	635	0.907	500	0.714	460	0.657	355	0.507
	Avg.		**0.764**		**0.657**		**0.711**		**0.529**
Average/Lateral:			**0.783**		**0.708**		**0.705**		**0.607**

APPENDIX J. Summary Tables of Field Information from Selected Sites in Ethiopia

Table J.1. Field Information for AG1

Crops	
Type:	Tomato, Pepper
Planting Date:	May, July (Eth)
Sp (cm):	30,30
Sr (cm):	80,80
Np	1,1
# Rows:	4,1
Soil	
Texture:	Sandy clay
Preparation:	Fair. 15 cm deep furrows
Water Supply	
Source:	Pond w/Plastic lining.
Lift Method:	Treadle Pump
Lift Required (m):	2.8
Horiz. Dist. Trans. (m):	8
Container Type:	Barrel
Approx. Vol. (L):	200
Time to Fill (min):	7
Max Water Level (m):	2.6
Min Water Level (m):	1.8
Salinity (dS/m):	-
Ph:	5.5
Filter:	Cloth over supply hose
Irrigation	
Duration (min):	52
Frequency:	Every evening
Start-up time (min):	-
Season Length:	about 3 months
No. Irri. per season:	Until pond is empty
System	
Date installed:	Mar 2000 (Eth)
Installed by:	IDE
No. of seasons used:	2
Mainline before filter (m):	2.1
Mainline after filter (m):	0.9
Mainline total length (m):	3
Approx. Area (m2):	62
Filter:	Cleaned every 2-3 days
Sub-main Length (m):	3.25
No. of valves:	1 (tap)
Valve quality:	
No. of laterals:	5
Lateral Length (m):	19
Lateral wall (um):	200?
Emitter type:	Micro-tube
Insertion length (cm):	5-10
Emitter spacing (cm):	30
Off season storage:	Left on the field all year

Table J.2. Field Information for EC1

Crops	
Type:	Kale
Planting Date:	Oct. 15, 2008
Sp (cm):	30
Sr (cm):	100
Np	0.5
# Rows:	4
Soil	
Texture:	Sandy clay
Preparation:	Good. Uneven surface
Water Supply	
Source:	Well
Lift Method:	Rope Pump, Carry
Lift Required (m):	-
Horiz. Dist. Trans. (m):	10
Container Type:	Bag
Approx. Vol. (L):	20
Time to Fill (min):	10
Max Water Level (m):	1.35
Min Water Level (m):	0.85
Salinity (dS/m):	1.75
Ph:	7
Filter:	None
Irrigation	
Duration(min):	34
Frequency:	4/day
Start-up time (min):	5
Season Length:	2 months
No. Irri. per season:	240
System	
Date installed:	Oct. 15, 2008
Installed by:	IDE
No. of seasons used:	0
Mainline before filter (m):	1
Mainline after filter (m):	0
Mainline total length (m):	1
Approx. Area (m2):	16
Filter:	Inline. Cleaned daily
Sub-main Length (m):	3.25
No. of valves:	1 (inline)
Valve quality:	No debris. ID = 6 mm.
No. of laterals:	4
Lateral Length (m):	5
Lateral wall (um):	200?
Emitter type:	Micro-tube
Insertion length (cm):	5-10
Emitter spacing (cm):	30
Off season storage:	Left on the field all year

Table J.3. Field Information for FTC1 and FTC2

Crops		
Type:	Onion	Onion
Planting Date:		
Sp (cm):	30	30
Sr (cm):	80	80
Np	0.17	0.17
# Rows:	10	10
Soil		
Texture:	Sandy Loam	Sandy Loam
Preparation:	Good	Excellent
Water Supply		
Source:	Well	Well
Lift Method:	Rope Pump	Rope Pump
Lift Required (m):	-	-
Horiz. Dist. Trans. (m):	-	-
Container Type:	Barrel	Barrel
Approx. Vol. (L):	200	200
Time to Fill (min):	~5	~5
Max Water Level (m):	1.8	1.8
Min Water Level (m):	1	1
Salinity (dS/m):		
Ph:	6.5	6.5
Filter:	None	None
Irrigation		
Duration(min):	98	57
Frequency:		
Start-up time (min):	6	2
Season Length:		
No. Irri. per season:		
System		
Date installed:		
Installed by:		
No. of seasons used:		
Mainline before filter (m):	1.8	1.8
Mainline after filter (m):	0.6	0.6
Mainline total length (m):	2.4	2.4
Approx. Area (m2):	79	79
Filter:	Clean, leaks	Clean, leaks
Sub-main Length (m):	7.9	7.9
No. of valves:	1	1
Valve quality:	ID small	ID small
No. of laterals:	10	10
Lateral Length (m):	10	10
Lateral wall (um):	200?	200?
Emitter type:	Micro-tube	Micro-tube
Insertion length (cm):	1-10	1-10
Emitter spacing (cm):	30	30
Off season storage:	See Fig. H.11	See Fig. H.11

Table J.4. Field Information for EC3

Crops	
Type:	Kale
Planting Date:	Oct. 29, 2008
Sp (cm):	30
Sr (cm):	100
Np	0.5
# Rows:	4
Soil	
Texture:	Sandy Loam
Preparation:	Good
Water Supply	
Source:	Well
Lift Method:	Bucket and Rope, Carry
Lift Required (m):	-
Horiz. Dist. Trans. (m):	125+
Container Type:	Bag
Approx. Vol. (L):	20
Time to Fill (min):	~30
Max Water Level (m):	1.35
Min Water Level (m):	0.95
Salinity (dS/m):	1.05
Ph:	6.5
Filter:	None
Irrigation	
Duration(min):	36
Frequency:	2/day
Start-up time (min):	4
Season Length:	
No. Irri. per season:	
System	
Date installed:	Sep. 2008
Installed by:	IDE
No. of seasons used:	0
Mainline before filter (m):	1
Mainline after filter (m):	-
Mainline total length (m):	1
Approx. Area (m2):	16
Filter:	Cleaned as necessary
Sub-main Length (m):	3.2
No. of valves:	1
Valve quality:	Dirt in valve. ID=5mm
No. of laterals:	4
Lateral Length (m):	5
Lateral wall (um):	200?
Emitter type:	Micro-tube
Insertion length (cm):	1-5
Emitter spacing (cm):	30
Off season storage:	Left on field

Table J.5. Field Information for EC4

Crops	
Type:	Peppers
Planting Date:	Oct. 22, 2008
Sp (cm):	30
Sr (cm):	80
Np	1
# Rows:	10
Soil	
Texture:	Sandy Loam
Preparation:	Excellent
Water Supply	
Source:	Well
Lift Method:	Rope Pump
Lift Required (m):	-
Horiz. Dist. Trans. (m):	5.8
Container Type:	Barrel
Approx. Vol. (L):	200
Time to Fill (min):	11
Max Water Level (m):	2
Min Water Level (m):	1.25
Salinity (dS/m):	-
Ph:	7.5
Filter:	None
Irrigation	
Duration(min):	65
Frequency:	2/day
Start-up time (min):	6
Season Length:	45 days
No. Irri. per season:	90
System	
Date installed:	May 08
Installed by:	IDE
No. of seasons used:	3 (crops harvested)
Mainline before filter (m):	5
Mainline after filter (m):	1
Mainline total length (m):	6
Approx. Area (m2):	74
Filter:	Cleaned every irrigation
Sub-main Length (m):	3.7 x 2 = 7.4
No. of valves:	1 (tap)
Valve quality:	-
No. of laterals:	10
Lateral Length (m):	10
Lateral wall (um):	200?
Emitter type:	Micro-tube
Insertion length (cm):	1-10
Emitter spacing (cm):	30
Off season storage:	Left on field

Table J.6. Field Information for AG2

Crops	
Type:	Tomato, Chickpea
Planting Date:	November 5, 2008
Sp (cm):	100
Sr (cm):	100
Np	1.67
# Rows:	4
Soil	
Texture:	Sandy Loam
Preparation:	Excellent
Water Supply	
Source:	Storage Pond
Lift Method:	Treadle Pump
Lift Required (m):	1.2
Horiz. Dist. Trans. (m):	6
Container Type:	Bag
Approx. Vol. (L):	20
Time to Fill (min):	1-2
Max Water Level (m):	1.2
Min Water Level (m):	0.75
Salinity (dS/m):	-
Ph:	5
Filter:	None
Irrigation	
Duration(min):	13
Frequency:	1/day
Start-up time (min):	1
Season Length:	-
No. Irri. per season:	-
System	
Date installed:	June 2008
Installed by:	IDE, farmer
No. of seasons used:	1 (crop harvested)
Mainline before filter (m):	1
Mainline after filter (m):	-
Mainline total length (m):	1
Approx. Area (m2):	19
Filter:	Cleaned every 3 days
Sub-main Length (m):	3.1
No. of valves:	1
Valve quality:	ID = 6 mm
No. of laterals:	4
Lateral Length (m):	6.1
Lateral wall (um):	200?
Emitter type:	Micro-tube
Insertion length (cm):	1-15
Emitter spacing (cm):	30
Off season storage:	Rolled and placed in box

Table J.7. Field Information for Golba4

Crops	
Type:	Kale
Planting Date:	November 7, 2008
Sp (cm):	30
Sr (cm):	100
Np	0.5
# Rows:	4
Soil	
Texture:	Sandy Loam
Preparation:	Fair
Water Supply	
Source:	Well (bore hole)
Lift Method:	Hand pump, carry
Lift Required (m):	-
Horiz. Dist. Trans. (m):	50
Container Type:	Bag
Approx. Vol. (L):	20
Time to Fill (min):	5
Max Water Level (m):	1.3
Min Water Level (m):	0.8
Salinity (dS/m):	-
Ph:	-
Filter:	None
Irrigation	
Duration(min):	13
Frequency:	2/day
Start-up time (min):	1.5
Season Length:	-
No. Irri. per season:	-
System	
Date installed:	October 30, 2008
Installed by:	IDE
No. of seasons used:	-
Mainline before filter (m):	1
Mainline after filter (m):	-
Mainline total length (m):	1
Approx. Area (m2):	18
Filter:	Cleaned 1/week
Sub-main Length (m):	3.1
No. of valves:	1
Valve quality:	ID = 6 mm
No. of laterals:	4
Lateral Length (m):	5.9
Lateral wall (um):	200?
Emitter type:	Micro-tube
Insertion length (cm):	5-15
Emitter spacing (cm):	30
Off season storage:	In house

Table J.8. Field Information for AGFTC

Crops	
Type:	Onion
Planting Date:	Oct. 15, 2008
Sp (cm):	30
Sr (cm):	80
Np	0.17
# Rows:	12
Soil	
Texture:	Sandy Clay
Preparation:	Fair
Water Supply	
Source:	Storage pond
Lift Method:	Treadle pump
Lift Required (m):	2.25
Horiz. Dist. Trans. (m):	4.5
Container Type:	Barrel
Approx. Vol. (L):	200
Time to Fill (min):	4
Max Water Level (m):	2.25
Min Water Level (m):	1.5
Salinity (dS/m):	-
Ph:	5.5
Filter:	None
Irrigation	
Duration(min):	42
Frequency:	-
Start-up time (min):	2
Season Length:	-
No. Irri. per season:	-
System	
Date installed:	Oct. 15, 2008
Installed by:	IDE
No. of seasons used:	-
Mainline before filter (m):	1.5
Mainline after filter (m):	0.45
Mainline total length (m):	1.95
Approx. Area (m2):	89
Filter:	Torn, not clean, leaks
Sub-main Length (m):	4.4 x 2 = 8.8
No. of valves:	2
Valve quality:	ID = 5 mm
No. of laterals:	12
Lateral Length (m):	10.1
Lateral wall (um):	200?
Emitter type:	Micro-tube
Insertion length (cm):	5-15
Emitter spacing (cm):	30
Off season storage:	-

Table J.9. Summary of Systems Installed, Evaluated, and Observed

Location ID	Coordinates	Name of Farmer	Work Completed
AG1	N7° 58.709’ E38° 41.237’	Bedhaso Tufa	Evaluation
AG2	N7° 58.958’ E38° 41.419’	Kufa Robel	Evaluation
AG3	N7° 57.831’ E38° 41.458’	Bati	Observation
AGFTC	N7° 57.684’ E38° 41.423’		Installation, Evaluation
ANFTC	N7° 21.718’ E38° 42.158’		Installation
DH1	N7° 38.405’ E38° 40.673’		Observation
EC1	N8° 00.249’ E38° 43.419’	Halima Baneta	Evaluation
EC2	N8° 00.208’ E38° 43.441’		Installation
EC3	N8° 00.290’ E38° 42.890’	Geno Negeso	Evaluation
EC4	N7° 58.482’ E38° 43.231’	Mekitu Bure	Evaluation
FTC1	N7° 57.847’ E38° 43.211’		Evaluation
FTC2	N7° 57.847’ E38° 43.211’		Evaluation
Golba1	N7° 50.342’ E38° 43.455’		Installation
Golba2	N7° 50.352’ E38° 43.483’		Installation
Golba3	N7° 50.209’ E38° 43.302’		Installation
Golba4	N7° 50.449’ E38° 43.405’	Shek Aman Silo	Evaluation
SDS	N9° 06.248’ E38° 59.139’		Observation

APPENDIX K. Valve Dimension Measurements

Objectives

Throughout field evaluations the hole through the valve stopcock was observed to be very small. It was recommended that this hole have the same inside diameter as the valve outlet inside diameter to reduce head loss. In order to determine if this was possible, the valve dimensions were measured.

Methodology

A random inline valve was selected for measurement. Measurements were taken using a micrometer with an accuracy of 0.01 mm. Five measurements were taken on the valve: the valve outlet inside and outside diameters, the diameter of the hole through the stopcock, and the stopcock inside and outside diameters.

Results and Discussion

The valve outlet inside and outside diameters were measured at 8.5 mm and 11.29 mm, respectively. The stopcock inside and outside diameters were 8.93 mm and 12.38 mm, respectively. The hole through the stopcock had a diameter of 5 mm.

Because the stopcock inside diameter is larger than the valve outlet inside diameter, the diameter of the hole in the stopcock could successfully be made equal to the outlet inside diameter. The question remains whether or not this would leave a sufficient seal when the valve is closed. In any case, the valve could be redesigned to accommodate the larger stopcock-hole diameter, without the addition of much more material.

APPENDIX L. Drip System Field Evaluation Form

Date:___________ Observer: _______________________ Location ID: ____________

Coordinates: __________________________ Name of Farmer: ____________________

Crops

Type	Planting Date	Sp	Sr	Np	# Rows

Soil: Texture: _______________________ Preparation: _________________________

Water Supply

Source: ______________ Lift Method: ___________ Lift Required: ______

Horz. Dist. Trans.: ____ Container Type: _________ Volume: _____ Time to Fill: ___

Max Water Level: _______ Min Water Level: ______ Salinity: _________ pH: _____

Filter Before Header Tank: ____

Notes: ____

Irrigation

Duration: ______ Frequency: _______ Start-up Time: ________

Season Length: _____________ No. of times operated per season: _____

Notes: ____

System

Date Installed: _________ Installed by: ________________ No. of seasons used: _____

Mainline Length (before filter): _______ after filter: ______ Total: _______

Approx. Area: ________ Filter: ________________________ Sub Main Length: ______

Valves: No. ____ Quality: ____

No. Laterals: ________ Lateral Length: ________ Lateral Wall Thickness: __________

Emitter Type: ____________ Insertion Length: ________ Emitter Spacing: __________

Off-Season Storage: ____

Comments (problems, clogging, leaks, practices, installation, etc.) __________________

____

____

System Layout, Topography, etc

Field Catchment

Emitter Location on the Lateral		Lateral Location on the Submain							
		Inlet		1/3 L		2/3 L		End	
		ml	lps	ml	lps	ml	lps	ml	lps
Inlet	A B								
	Ave.								
1/3 L	A B								
	Ave.								
2/3 L	A B								
	Ave.								
End	A B								
	Ave.								

Discharge test volume collected in ___________