Global Uniformity of Trickle Irrigation Systems

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ABSTRACT

A simulation model for the study of trickle irrigation uniformity was developed which treats the various equipment, system and other factors known to influence emitter flow rate variation. The model provides a tool for the assessment of global trickle uniformity in the sense that the assessment need not be spatially or otherwise restricted. A number of simulations were made to determine the sensitivity of global trickle uniformity to each of the determining factors. Emitter plugging, the number of emitters per plant, and emitter manufacturing variation are the most significant factors influencing the uniformity of trickle irrigation systems.

INTRODUCTION

The uniformity of water application to plants by trickle irrigation systems is an important concept affecting the design and operation of these systems (Howell et al., 1980; Merriam and Keller, 1978). Many researchers have studied trickle irrigation uniformity, though most assessments have been limited in scope. Studies have been restricted either to a typical lateral (e.g., Howell and Hiler, 1974; Wu and Gitlin, 1974), or to only a few of the factors known to affect trickle

irrigation uniformity (e.g., Nakayama and Bucks, 1981; Zur and Tal, 1981). Borrowing a term from mathematics, uniformity studies that are spatially or otherwise restricted can be said to assess *local* uniformity. In contrast, a *global* study of trickle uniformity would consider the wide variety of factors affecting uniformity; pressure differences due to elevation changes or friction losses throughout the entire pipe network; spatial and temporal variations in water temperature; emitter response to water temperature and pressure; manufacturing (unit to unit) variation in emitters and pressure regulators; the number of water application points per plant; and the degree and extent of emitter clogging.

A review of selected studies on trickle irrigation uniformity is summarized in Table 1. Clearly, most prior work on trickle uniformity is local in nature. No study addresses all of the factors influencing uniformity, and only three consider as many as five variables. While many of the studies treat lateral line hydraulics, only two treat both lateral and manifold hydraulics. Little work has been done on the effects of water temperature variation and emitter plugging.

The objectives of the present work are: (a) to introduce the notion of global uniformity in trickle irrigation; (b) to present a model which can be used in simulation studies of global trickle uniformity; and (c) to give some indication of the relative importance of the various factors influencing uniformity.

THEORETICAL DEVELOPMENT

Following the practice of Bralts (1983) and Solomon and Keller (1978), the object of study is taken to be the

TABLE 1. FACTORS CONSIDERED IN SELECTED TRICKLE UNIFORMITY STUDIES

#	Reference	Emitter flow rate response to Pressure	Emitter flow rate response to Water temp.	Manufacturing variation Emitter	Manufacturing variation Pressure regulat.	Hydraulics Lateral	Hydraulics Manifold	No. of emitters per plant	Variations in water temperature Spatial	Variations in water temperature Temporal	Emitter plugging Full	Emitter plugging Partial
1.	Bralts et al., 1981a	X		X		X						
2.	Bralts et al., 1981b	X				X		X			X	X
3.	Braud and Soom, 1981	X				X						
4.	Howell and Hiler, 1974	X				X						
5.	Karmeli et al., 1978	X		X		X						
6.	Nakayama and Bucks, 1981			X				X			X	
7.	Nakayama et al., 1979			X				X				
8.	Parchomchuk, 1976	X	X						X			
9.	Perold, 1977	X				X						
10.	Solomon, 1977	X	X	X								
11.	Solomon, 1979	X		X		X	X	X				
12.	Solomon and Keller, 1978	X		X		X	X	X				
13.	Wu and Gitlin, 1974	X				X						
14.	Wu and Gitlin, 1977						X					
15.	Wu and Gitlin, 1983			X		X						
16.	Zur and Tal, 1981	X	X			X			X			

trickle system subunit: an independently controlled portion of a trickle system, consisting of emitters, lateral lines, a manifold feeding the lateral lines, and perhaps pressure regulators at the lateral inlets. It is assumed that the manifold is fed at one end, and that laterals extend from one side of the manifold. Cases involving center-fed laterals and manifolds are covered by straight forward generalizations of the theory developed here. Throughout the following, M denotes the relative position along the manifold, ranging from zero at the inlet to unity at the downstream end. Similarly, L is the relative distance along a lateral. Any position within the subunit can be identified by the coordinate pair (M,L). The subunit inlet is at (0,0), while the downstream end of the last lateral on the manifold is at (1,1).

Emitter Flow Rate

The flow rate from individual emitters depends on operating pressure, water temperature, manufacturing variation, and the degree to which the emitter is plugged. It is usually assumed that over some range of pressure (H) the emitter flow rate (q) is proportional to H^x. The exponent x characterizes the emitter flow regime, and normally falls between zero and one. The emitter flow rate may be specified by:

$$q = K \, K_v \, K_T \, K_p \, H^x \quad \dots \dots \dots \dots \dots \dots \dots \dots \dots [1]$$

where
  K = constant of proportionality
  K_v = adjustment due to manufacturing variability
  K_T = adjustment due to water temperature
  K_p = adjustment due to emitter plugging

Manufacturing variation of emitters is characterized by v_e, the emitter coefficient of variation. v_e is defined as the ratio of standard deviation to mean emitter flow rate, measured at a standard pressure and temperature, with no plugging. v_e is typically below 0.15, though values as high as 0.40 have been measured. Solomon (1977, 1979) presented values of x and v_e for a number of different types of emitters. If it is assumed that manufacturing variation results in normally distributed flow rates, then a stochastic expression for K_v is

$$K_v = 1 + v_e Z_1 \quad \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots [2]$$

where Z_1 is a value drawn at random from the standard normal variate.

Water temperature can influence emitter flow rate through changes in the viscosity of water, the size of emitter passages, or in the properties of the resilient materials used in some emitters. The studies of Parchomchuk (1976), Solomon (1977) and Zur and Tal (1981) indicate that, with a few exceptions, the effect of water temperature on emitter flow rate is roughly linear. Parchomchuk (1976) noted that for some microtube emitters, the flow regime changes from laminar to turbulent near a critical temperature. Even for these emitters, though, flow was linear with temperature except near the critical temperature. Flow rate dependence on water temperature may be characterized by k_T, the percent increase in flow rate per °C increase in water temperature. (For some emitters, flow rate decreases with increasing temperature. Hence k_T may be negative.) If T is water temperature, and T_n is the temperature at which the emitter exhibits nominal

characteristics, then

$$K_T = 1 + (k_T/100)(T - T_n) \quad \dots \dots \dots \dots \dots \dots \dots \dots [3]$$

Published data (Parchomchuk, 1976; Solomon, 1977; Zur and Tal, 1981) indicate that k_T may range from −0.68 to 6.80, though k_T does not usually exceed about 1.4.

Bralts et al. (1981b) noted that emitter plugging could be either full or partial. They defined partial plugging as a reduction in emitter flow rate due to a decrease in the size of the emitter flow passage. Complete plugging, of course, reduces the flow rate to zero. Let P_p be the portion of the emitters that are either partially or fully plugged, and P_c be the portion of plugged emitters that are completely plugged. Let α be the fracton of the normal emitter flow rate achieved by the partially plugged emitters. Finally, let U be a value drawn at random from a variate uniformly distributed on the interval [0,1].

$$
\begin{aligned}
K_p = \ & 1 \quad \text{for } U \geqslant P_p \\
& 0 \quad \text{for } U \leqslant P_p P_c \\
& \alpha \quad \text{for } P_p P_c < U < P_p \quad \dots \dots \dots \dots \dots \dots [4]
\end{aligned}
$$

Trickle system uniformity, as related to crop yields, depends on the uniformity of water application to each plant. Since plants often receive water from more than one emitter, this may not equal the uniformity of individual emitter application rates. Solomon (1979) noted that with multiple emitters per plant, the uniformity of application per plant is higher than the uniformity of application per emitter. Bralts et al. (1981b) and Nakayama and Bucks (1981) found that this effect is particularly important when emitter plugging is considered. If n is the number of emitters per plant, then q_t, the total flow rate delivered to a plant, is given by

$$q_t = (K \, K_T H^x) \sum_{i=1}^{n} (K_{v_i} \, K_{p_i}) \quad \dots \dots \dots \dots \dots \dots \dots [5]$$

where K_{v_i} and K_{p_i} are the manufacturing variation and plugging adjustment factors determined for individual emitter i. It is the uniformity of q_t that is significant.

Equations [1] and [5] presume that the various factors influencing emitter flow rate do so independently. While this is a reasonable premise for the current study, some degree of interdependence probably does exist. The experience of the author and others (V.F. Bralts, personal communication) indicates that v_e may change somewhat with H, and occasionally with T. Though the range of pressure for which x remains fixed may be quite broad, x is, in general, dependent on H. x may also change with T, as in the case of the microtubes studied by Parchomchuk (1976), or emitters incorporating resilient materials whose properties change with temperature. These observations notwithstanding, equations [1] and [5] will be accepted as valid, and used to (stochastically) determine individual emitter and plant application rates once operating pressure and water temperature are known. The following sections address the distribution of pressure and temperature within a trickle irrigation subunit.

Subunit Hydraulics

As noted above, manifold and lateral line hydraulics

are not often treated jointly. Solomon and Keller (1978) presented a closed form expression for the pressure (H) at any point within a trickle subunit, H(M,L). Their derivation was based on an empirical fit to the shape of the friction loss curves observed for typical trickle laterals, and required some simplifications regarding the changes in lateral line hydraulics with position on the manifold. More recently, Bralts (1983) used the finite element method to analyze this problem. He presented an approximate closed form expression used to initialize the finite element solution. The derivation presented below results in a closed form solution that avoids some of the simplifying approximations in previous work.

Consider first the change in pressure along an individual trickle lateral line due to friction loss. Wu and Gitlin (1974) and others have shown that the pressure at relative position L is given by

$$H(L) = H(0) - F_\ell[1-(1-L)^{a+1}] \quad \ldots\ldots\ldots\ldots\ldots [6]$$

where

$H(L)$ = pressure at relative position L
$H(0)$ = pressure at the inlet
F_ℓ = total friction loss in the lateral
L = relative position along the lateral
a = constant

The constant a in equation [6] is, in fact, the flow rate exponent in the friction loss formula used. Watters and Keller (1978) presented data showing that friction losses in trickle tubing is most correctly expressed by the Darcy-Weisbach equation when combined with the Blasius formula for the friction factor, which results in a flow rate exponent of 1.75. Thus equation [6] may be written

$$H(L) = H(0) \left\{ 1-g[1-(1-L)^{2.75}] \right\} \quad \ldots\ldots\ldots\ldots [7]$$

where

g = lateral friction loss ratio $F_\ell/[H(0)]$

The emitter discharge per unit length of lateral is a function of pressure. The discharge $q(L)$ from an incremental lateral length dL located at position L is given by

$$q(L) = K'[H(L)]^x dL \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots [8]$$

where K' is a constant of proportionality. The total flow rate for the lateral (Q) can be found by integrating equation [8]. Making the variable substitution J = (1-L),

$$Q = K'[H(0)]^x \int_0^1 [1-g(1-J^{a+1})]^x dJ \quad \ldots\ldots\ldots [9]$$

For most emitters, $0<x<1$, rendering equation [9] problematical. A series solution can be obtained by integrating the binomial expansion of the integrand, term by term. This leads to the approximate result

$$Q = K'[H(0)]^x(1-g)^x \left\{ 1+[x/(a+1)][g/(1-g)] \right\} \quad \ldots [10]$$

The bionomial expansion series can be shown to converge only for $g \leqslant 0.5$, hence this restriction also applies to equation [10]. The expression is exact for x = 1 and x = 0. An examination of the higher order terms in the series solution shows that when a is taken as 1.75, equation [10] is correct to within 2%, with the greatest errors being produced when x and g are both near 0.5.

Now suppose that two identical laterals are operated at initial pressures $H_1(0)$ and $H_2(0)$, resulting in flow rates Q_1, and Q_2, friction losses F_1 and F_2, and lateral friction loss ratios g_1 and g_2 respectively. It will be useful to develop an expression for g_2 in terms of the other quantities. Since F is proportional to Q^a for each lateral, $(F_2/F_1) = (Q_2/Q_1)^a$, which leads to

$$g_2 = g_1 k^{ax-1} A^{a(x-1)} B^a \quad \ldots\ldots\ldots\ldots\ldots\ldots [11]$$

where

k = $[H_2(0)/H_1(0)]$
A = $[(1-g_2)/(1-g_1)]$
B = $[(a+2)(1-g_2) + xg_2]/[(a+2)(1-g_1) +xg_1]$

Since g_2 appears on both sides of equation [11], it is only implicitly determined. The form of equation [11] suggests that an interation scheme on g_2 might be useful. Unfortunately, this produces an oscillating divergent series. Judiciously reducing the size of the change in g_2 at each step, however, results in a series of estimates that converges slowly to the solution of equation [11]. Examination of solutions for a range of conditions lead to the following approximate expression for g_2.

$$g_2 = g_1 k^{(ax-1+b)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots [12]$$

where

b = $(-0.83x)(x-1/a)(3.14-x)g_1^c$
c = $1.14 - 0.28x$

The form of equation [12] is suggested by two observations: first, whenever g_2 is approximately equal to g_1, A and B in equation [11] are both approximately one; second, the error introduced by assuming A = B = 1 will be dependent on k. Once g_2 for a given condition has been determined by solving equation [11], the value of b that makes equation [12] exact may be calculated. The forms of equations [10] and [11] imply that b must equal zero whenever x = 0 or x = 1/a. The complete expression for b was derived from an exploration of the effects of x and g_1 on b. The coefficients of this expression were fitted for a = 1.75. The expression is exact for x = 0 and x = 1/a, and is correct to within 1% for $k \leqslant 2$, which should cover conditions in most trickle system subunits. Even for k as large as 3, the maximum error is just over 3%.

Equations [7] and [12] can be combined to describe the pressure changes due to friction losses for laterals within a trickle irrigation subunit. A description of manifold hydraulics is also needed in order to specify the lateral inlet pressures. Wu and Gitlin (1977) analyzed constant diameter trickle manifolds in a manner similar to laterals by treating each lateral on the manifold as a "large emitter." Equation [6], with L replaced by M, should apply to manifold pressure changes due to friction losses. On the assumption that the Hazen-Williams formula for friction loss holds for manifold pipes, Wu and Gitlin (1977) used the value a = 1.852 for manifolds. Watters and Keller (1978), however, claimed that a = 1.75 is appropriate for small diameter plastic pipe as well as trickle tubing. They recommended using a = 1.75 for plastic pipe with nominal diameter less than 125 mm. The difference is probably not significant, since both vlaues of a give similar results. The maximum difference between $[1-(1-L)^{1.75}]$ and $[1-(1-L)^{1.825}]$ is only about 3%. In the present study, a = 1.75 has been used

for both laterals and manifolds. Thus pressure changes due to friction losses in constant diameter manuifolds may be described by

$$H(M,0) = H(0,0) - F_m[1-(1-M)^{2.75}] \ldots \ldots \ldots [13]$$

where

M = relative position along the manifold
F_m = total friction loss in the manifold

Manifolds need not be constructed of a constant diameter, of course. "Tapered" manifolds use smaller pipe sizes downstream as the flow in the manifold decreases. A common approach to designing tapered manifolds is to select pipe sizes so as to maintain a nearly constant head loss per unit manifold length (Solomon and Keller, 1978). For fully tapered manifolds, then, $H(M,0) = H(0,0) - M F_m$. This can be expressed in a form similar to equation [13]:

$$H(M,0) = H(0,0) - F_m[1-(1-M)] \ldots \ldots \ldots \ldots [14]$$

The similarity in form between equations [13] and [14] suggests that the exponent of (1-M) might be related to an indocator of how the manifold has been constructed. Let τ be a dimensionless measure of the degree to which the manifold is tapered. τ = 0 for a constant diameter manifold, and τ = 1 for a fully tapered manifold. Using this parameter, equations [13] and [14] may be combined.

$$H(M,0) = H(0,0) - F_m[1-(1-m)^d] \ldots \ldots \ldots \ldots [15]$$

where

d = 1 + a(1-τ)
τ = measure of relative manifold taper

Another type of manifold construction employs pressure regulators to minimize variation in lateral inlet pressure. When regulators are used, H(M,0) = R, where R is the regulators' output pressure. Regulators are available with either fixed or adjustable outlet pressures. Regulators may be placed at the head of each lateral, or one regulator may control three to five laterals tied together (S. Hawkins and J. Tucker, personal communication). The latter approach is common with adjustable regulators, since they tend to be designed for higher flow rates. Regulator output pressure depends on model, inlet pressure, and flow rate, though the dependency on inlet pressure can be quite slight. For example, the outlet pressure of one model varies only 7 kPa (1 psi) over a 455 kPa (65 psi) range of inlet pressures, (Anon., 1983). For a given model of fixed regulators, the nominal output pressure decreases as the flow rate through the regulator increases. This should not be a limitation, however, since regulated laterals are not expected to change flow rate. Thus the major source of variation in regulated lateral inlet pressure is probably unit to unit variation in the regulators themselves. One manufacturer uses 100% water testing to ensure that unit to unit variation in output pressure does not exceed ±6% (Anon., 1982). Typical coefficients of variation (ratio of standard deviation to mean) for other pressure regulators are about 0.05 (D.W. Hendrickson, personal communication). Adjustable pressure regulators can be adjusted to the required outlet pressure after installation. The variations in these instances will depend on the accuracy of the pressure gauge used and the

diligence of the worker. R.D. Grassick (personal communication) estimates that with care, an output pressure coefficient of variation of 0.02 may be attained.

Assuming inlet pressures of regulated trickle laterals are normally distributed, they may be described by the stochastic equation

$$H(M,0) = R(1+v_R Z_2) \ldots \ldots \ldots \ldots \ldots \ldots [16]$$

where

R = nominal regulator outlet pressure
v_R = pressure regulator coefficient of variation
Z_2 = a value drawn at random from the standard normal variate

A single expression, valid for all types of manifolds, may be formed by using H(0,0) for R, setting F_m = 0 for regulated laterals, and v_R = 0 for unregulated ones.

$$H(M,0) = H(0,0)[1+v_R Z_2] - F_m[1-(1-M)^d] \ldots [17]$$

The development thus far has considered only pressure changes due to friction loss. However, elevation changes throughout the subunit will also influence emitter operating pressures. Let E(M,L) be the elevation at position (M,L), and ΔE(M,L) = E(0,0) − E(M,L). It is commonly assumed that the effects of friction losses and elevation differences are independent (Howell et al., 1980). If E and H are measured in the same units, then the operating pressure at (M,L) will be the sum of ΔE(M,L) and the pressure determined by a combination of equations [7], [12], and [17]:

$$H(M,L) = H(M,0)\left\{ 1-g_m[1-(1-L)^{a+1}] \right\} + \Delta E(M,L)$$
$$\ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots [18]$$

$$g_m = g_\ell [H(M,0)/H(1,0)]^{(ax-1+b)}$$

$$g_\ell = F_\ell/H(1,0)$$

$$H(1,0) = H(0,0) - F_m$$

$$H(M,0) = H(0,0)[1+v_R Z_2] - F_m[1-(1-M)^d]$$

where

g_m = head loss ratio for lateral at position M
g_ℓ = head loss ratio for last lateral on manifold
F_ℓ = friction loss in last lateral on manifold
F_m = friction loss in the manifold
a = 1.75
b = $(-0.83x)(x-1/a)(3.14-x)g_1^c$
c = 1.14 − 0.28x
d = 1 + a(1-τ)

It will be convenient to define F as the total subunit friction loss, $F = F_m + F_\ell$. To specify the pressure distribution in a trickle subunit using equation [18], the following must be specified: the constants H(0,0), F, (F_m/F_ℓ), v_R and τ; and the function ΔE(M,L).

Water Temperature Variation

Because the flow rate from some emitters is sensitive to water temperature (Solomon, 1977), the variation in water temperature throughout the subunit must be considered. Trickle laterals, and sometimes manifolds, are often placed above ground, and hence are subject to weather changes and solar radiation. The water temperatures in exposed laterals should increase with distance from the inlet. Furthermore, the decrease with
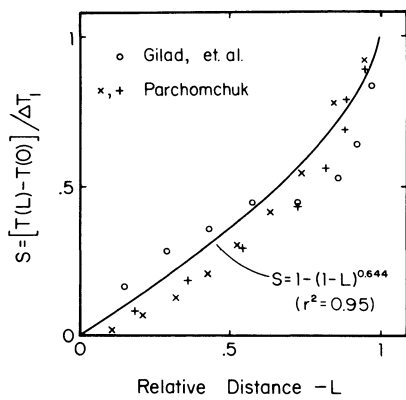
Fig. 1—Water temperature increase in trickle irrigation laterals.

distance of flow rate within the lateral suggests that the rate of temperature increase should also increase with distance along the lateral. Temperatures as high as 77°C (170°F) at the end of laterals have been reported (Anon., 1975). Parchomchuk (1976) observed temperature increases of up to 19°C (34°F) in laterals laid on the soil surface, and 6°C (11°F) for a lateral buried 150 mm (6 in.) below the surface, while Gilad et al. (1968) observed a 12°C (22°F) rise in temperature for an exposed lateral. These reports also present water temperature as a function of distance along the lateral for three exposed laterals. Fig. 1 displays these data in dimensionless form. The expression below provides a good fit ($r^2 = 0.95$) to these data:

$$T(L) = T(0) + \Delta T_\varrho [1-(1-L)^{0.644}] \quad \ldots \ldots \ldots [19]$$

where

  T(L) = water temperature at relative lateral
      position L

  ΔT_ℓ = T(1) − T(0)

If all laterals are assumed to have the same water temperature change ΔT_ℓ, and the manifold experiences a temperature change ΔT_m, then the water temperature T at any point (M,L) in the trickle subunit will be given by

$$T(M,L) = T(0,0) + \Delta T_m [1-(1-M)^{0.644}]$$
$$+ \Delta T_\varrho [1-(1-L)^{0.644}] \quad \ldots \ldots \ldots \ldots \ldots \ldots [20]$$

While equation [20] was developed for water temperature increases during the day, it may also apply for temperature decreases that might occur. At night, the lateral should radiate heat from the water to the surrounding colder environment, reducing water temperature. This effect would be most pronounced near the end of the lateral where water velocities are the lowest. Thus equation [20] is qualitatively correct for temperature decreases as well as increases, and in the absence of evidence to the contrary, may be assumed to hold regardless of the signs of ΔT_m and ΔT_ℓ.

Parchomchuk (1976) noted that water temperatures may be expected to vary with time as well as position. ΔT_ℓ for one lateral changed from 16°C (29°F) on a bright sunny day to 6°C (11°F) on a cloudy day. His supply water temperature varied 22°C (40°F) between spring and summer. Although data in this area are scarce, some assumptions regarding temporal variation

in water temperature are required to evaluate water temperature effects on subunit uniformity. In the following, $\Delta T = \Delta T_m + \Delta T_\ell$.

Water temperatures are subject to diurnal, short term day to day, and long term seasonal variations. To predict the water temperature distribution within a subunit for a particular irrigation event, water temperature information on all three time scales would be required. When considering, however, the uniformity of cumulative application from multiple irrigation events, temporal variations in ΔT will, to some extent, average out. Since the influence of water temperature on emitter flow rate is linear (cf. equations [1], [3]) cumulative application over some period will be influenced by the average water temperature over that period. Seasonal application, for example, is determined by the expected value of water temperature over the irrgation season.

From the standpoint of crop yield, though, it is probably not wise to mathematically average out temporal variations in application over two long a period. A deficit may have done its damage long before a compensating, but tardy, excess application comes along. This is particularly true for trickle irrigation, which may wet considerably less soil volume than other irrigation methods.

The approach taken here is to assume that short term fluctuations in ΔT are self-compensating, but that the longer term seasonal effects are not. This implies that uniformity evaluation should be done using water temperature values typical to the most water critical stage of growth. Thus the water temperature model equation [20] will be initialized by specifying such typical values for T(0,0), ΔT, and ($\Delta T_m/\Delta T_\ell$). Note that the critical growth stage need not coincide with extreme values of ΔT, since the crop canopy may shade the laterals then. In some cases, young orchards for instance, canopy shading is not a factor.

PROCEDURE

The uniformity of the trickle irrigation subunit is determined by the distribution of q_t as determined in equation [5]. This will involve a combination of the distributions of H, T, K_T and K_p within the subunit. While techniques for describing and combining these individual distributions are available (Solomon, 1983), estimating the properties of the distribution of q_t by simulation is simpler and entirely adequate for present purposes. The simulation process may be summarized as follows.

  1. Specify values for emitter and subunit parameters.

  2. Choose N pairs (M,L), specifying N positions within the subunit.

  3. For each position:

      (a) Using equations [18] and [20], compute H(M,L) and T(M,L), the pressure and water temperature at (M,L).

      (b) Using equations [2] and [4], determine n values each for the manufacturing variation and plugging adjustment factors K_v and K_p.

      (c) Using equation [15], determine the application rate for the plant (group of n emitters) located at (M,L).

Step 2 requires further elaboration. Values for M and L could be selected at random (and there are several ways

to accomplish this), or could be deterministically specified to ensure positions uniformly dispursed throughout the subunit. The latter approach was used in present study. Twenty five laterals were chosen, with their positions along the manifold determined by $M = [(i-1)/24]$ for $i = 1$ to 25. Along each lateral, forty plant locations were determined by $L = [(j-1)/39]$ for $j = 1$ to 40. This results in a sample size of $N = 1000$ locations, large enough to make reliable estimates of subunit uniformity. Suppose μ, σ, and ν are the mean, standard deviation and coefficient of variation for the population of q_t values, and m, s, and V are estimates thereof computed from the simulated sample. For $N = 1000$, 95% confidence limits (Walpole, 1968) on μ and σ are (m $\pm$ 0.062s) and (0.959s, 1.047s) respectively. For $\nu \sim 0.2$, 95% confidence limits on μ are (V $\pm$ 0.01).

While it is common for scientific computer languages to include a built-in function for providing uniformly distributed (pseudo) random numbers, some adjustment may be necessary to produce normally distributed random numbers. A technique taken from Law and Kelton (1982) was used for this purpose. Their algorithm takes pairs of observations (U_1, U_2) drawn from a variate uniformly distributed on [0,1] and transforms them into a pair of observations (Z_1, Z_2) drawn from a standard normal variate. The steps of the process are:

1. Generate U_1 and U_2.
2. $u_1 = 2U_1 - 1$. $u_2 = 2U_2 - 1$. $w = u_1^2 + u_2^2$.
3. If $w > 1$ then return to step 1.
4. $W = [(1-2 \ln w)/w]^{0.5}$.
5. $Z_1 = u_1 W$. $Z_2 = u_2 W$.

A number of simulation runs were made for this study. Some of the subunit parameters were held constant for all runs. It was assumed that all pressure differences were due to friction losses, so the terrain function $\Delta E(M,L) = 0$. Thus F represents the maximum pressure differential throughout the subunit. Since the standard water temperature for measuring emitter flow characteristics is 20°C (Parchomchuk, 1976; Solomon, 1977), it was assumed that $T(0,0) = T_n = 20°C$. Because the temperature change in the manifold will usually be considerably smaller than that in the laterals, ΔT_m and ΔT_ℓ were taken as 0 and 20°C respectively.

Low, medium, and high values were assigned to each parameter (except those dealing with emitter plugging), indicating the range of conditions that might be expected in practice. Table 2 lists these parameter values. Various types of plugging were simulated using different combinations of values for P_p, P_c, and α, as shown in Table 3. Three series of simulations were made. The first series consisted of a "base" run with all parameters in Table 2 set to their medium levels, and without plugging, followed by simulations wherein one parameter at a time was changed to its low and then high value. The second series was the same as the first, except that the plugging parameters were set to simulate medium mixed plugging. The third series simulated the plugging conditions of Table 3, with all other parameters set to their medium levels.

RESULTS

Subunit uniformity was quantified by computing the coefficient of variation (V) for the q_t values. The results

TABLE 2. PARAMETER VALUES FOR SIMULATIONS

Description	Symbol	Low	Medium	High
Emitter exponent	x	0.0	0.5	1.0
Emitter coefficient of mfg. var.	v_e	0.025	0.075	0.125
Water temperature sensitivity factor	k_T	-0.4	0.0	0.6
Number of emitters per plant	n	1	4	8
Relative subunit pressure differential	F/[H(0,0)] *	0.1	0.2	0.3
Ratio of manifold to lateral friction loss	F_m/F_ℓ	0.5	1	2
Relative degree of manifold taper	τ	0.0	0.5	1.0
Regulator coefficient of mfg. var.	v_R *	0.02	0.05	0.08

*The conventions associated with equation [17] require that $v_R = 0$ whenever
$F \neq 0$, and $F = 0$ whenever $v_R \neq 0$.

TABLE 3. PARAMETER VALUES TO SIMULATE VARIOUS PLUGGING CONDITIONS

Condition	Portion of emitters fully or partially plugged (P_p)	Portion of plugged emitters fully plugged (P_c)	Relative flow from partially plugged emitters (α)
Full plugging only:			
None	0.0	0.0	1.0
Medium (25%)	0.25	0.10	1.0
High (50%)	0.50	0.10	1.0
Partial plugging only:			
None	0.0	0.0	1.0
Medium	0.25	0.0	0.9
High degree*	0.25	0.0	0.8
High extent*	0.50	0.0	0.9
Mixed plugging:			
None	0.0	0.0	1.0
Medium	0.25	0.10	0.9
High	0.50	0.10	0.8

*"Degree" refers to how much the flow from partially plugged emitters is reduced,
while "Extent" refers to the number of emitters in the subunit that are affected
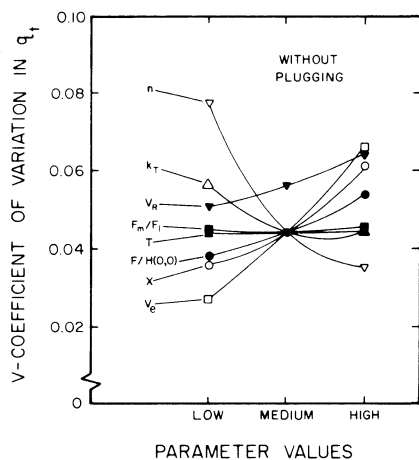by partial plugging.

Fig. 2—Sensitivity of subunit uniformity to changes in parameter values, in the absence of plugging.
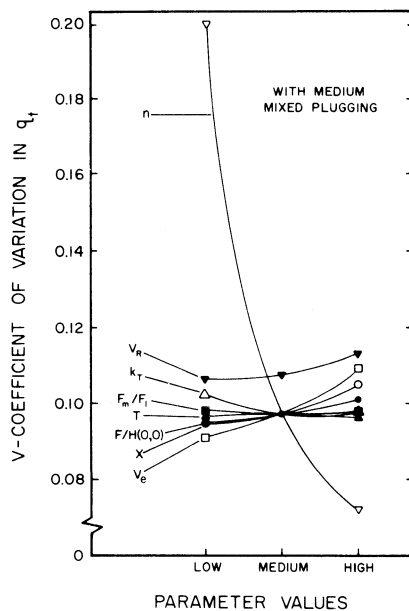

Fig. 3—Sensitivity of subunit uniformity to changes in parameter values, in the presence of medium mixed plugging.
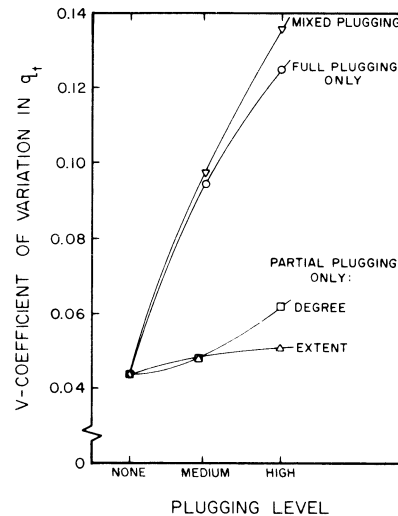

Fig. 4—Sensitivity of subunit uniformity to type and level of plugging, with other parameters set to medium levels.

of the first, second, and third series of simulations are illustrated in Figs. 2, 3, and 4 respectively. Increases in x, v_e, F, and v_R generally caused increases in V, while increases in k_T and n decreased V. Changes in $[F_m/F_l]$ and τ had little or no effect on V. Any type of plugging increased V.

The single most significant factor influencing subunit uniformity is plugging. The base run V in the presence of plugging is nearly twice that observed in the absence of plugging. Furthermore, the presence of plugging seems to reduce the sensitivity of V to all other factors except n. As shown by Bralts et al. (1981b) and Nakayama and Bucks (1981), there is a strong interaction between the number of emitters per plant and plugging. Complete plugging of only a few emitters is more significant than partial plugging of larger numbers of emitters. The degree of reduction in flow from partially plugged emitters is relatively more important than the extent to which emitters throughout the entire subunit are affected (Fig. 4).

In the presence of plugging (Fig. 3), the parameter of most significance is n, the number of emitters per plant. With medium mixed plugging, going from one to four emitters per plant reduces V by a factor of more than two. Even without plugging, V is strongly influenced by n, decreasing by a factor of 1.75 with a change of n from 1 to 4. This sensitivity is the greatest for small n.

The next most significant factors seem to be v_e, the emitter coefficient of manufacturing variation, and k_T, which characterizes the emitter flow rate response to water temperature. The low, medium and high values of v_e in Table 2 were taken from ASAE EP405 (ASAE, 1980) as the midpoint of the ranges classified therein as good, average, and marginal for point source emitters. The sensitivity of V to v_e indicated in Figs. 2 and 3 is for n = 4. As noted by Solomon and Keller (1978) and others, there is an interaction between n and v_e similar to that between n and plugging. The effect of v_e on V would be much stronger for n < 4, and less severe for n > 4. The influence of k_T on V is, of course, dependent on ΔT, taken as 20°C in the present study. Negative values of k_T,

implying that emitter slow rate decreases with water temperature, have a stronger impact on V than positive ones. Emitters for which k_T is positive will tend to have higher flow rates at the end of lateral lines where temperatures are the highest, counter-balancing the effect of lower pressures there due to friction.

The effects of emitter exponent (x) and relative head loss throughout the subunit [F/H(0,0)] are similar, a result not unexpected in light of the emitter discharge equation [1]. Recall that in the simulations done here (for which $\Delta E(M,L) = 0$), F is a surrogate for the total pressure differential throughout the subunit. For fixed total differential, a shift in the magnitudes of F and ΔE is not expected to affect V greatly, although it may influence the shape of the distribution of emission rates in other ways. This is supported by the observation that changes in τ and $[F_m/F_l]$, which also change the shape of the distribution of pressures within the subunit (Solomon and Keller, 1978), cause negligible changes in V.

The regulator coefficient of variation (v_R) is less important than emitter coefficient of variation (v_e), unless large n greatly mitigates the influence of v_e. While v_e is related directly to flow rate variation, v_R relates only to variations in pressure, the significance of which is reduced so long as x < 1. The v_R sensitivity curves of Figs. 2 and 3 do not pass through the common point of the other curves because F for these runs was fixed at F = 0.2, so any $v_R \neq 0$ represents an additional source of variation within the subunit. This is representative of the field situation where the use of pressure regulators to eliminate pressure differences along the manifold allows greater differences along the laterals for the same total differential. As with the other factors, sensitivity of V to v_R is reduced in the presence of plugging.

SUMMARY AND CONCLUSIONS

The uniformity of water applied to each plant by a trickle irrigation system depends on many factors, related to equipment characteristics, system design and maintenance (plugging). Traditional assessments of

trickle uniformity are *local* in the sense that they are spatially or otherwise restricted. A *global* assessment of trickle uniformity would consider all the factors that influence emitter uniformity. Relevant equipment factors are emitter flow rate response to operating pressure and water temperature, and manufacturing variation in emitters and pressure regulators. System factors include manifold and lateral line hydraulics, pressure differences due to friction losses and elevation differentials, the number of emitters per plant, and spatial and temporal variations in water temperature. Other important factors influenced by system maintenance are the extent of full plugging and the degree and extent of partial plugging.

A simulation model was developed to enable the assessment of global trickle uniformity under various circumstances. The model includes a closed form expression for the pressure at any point within the subunit. The model components involving the distribution of water temperature and plugging are probably the weakest. Water temperature changes are assumed to follow empirically observed patterns, but the underlying data base is very small. The model assumes that there is no relationship between location within the subunit and the chance of plugging. Some field observations (Bralts et al., 1981b) support this assumption, but it may not be valid under all conditions. Since plugging and water temperature effects are among the more significant factors influencing subunit uniformity, further work in these areas would be desirable.

The order of importance of those factors affecting subunit uniformity was found to be (most important factors first): plugging; number of emitters per plant; emitter coefficient of variation; emitter exponent; emitter flow response to water temperature; subunit pressure differences; pressure regulator coefficient of variation; ratio of manifold to lateral friction loss; and degree of manifold taper. This ranking is not absolute, since it depends on the range of values associated with each parameter. In a particular instance, some alteration to this list may be appropriate. However, the parameter values analyzed were chosen to represent the range of values usually encountered in practice, so the ranking as presented should be correct for most circumstances.

References

1. Anonymous. 1975. Drip system insuring future water for Arizona pecans. Drip Irrigation Farming, pp 6-8.

2. Anonymous. 1982. Product catalog. Senninger Irrigation, Inc., Orlando, FL.

3. Anonymous. 1983. Drawing number E9000L052. Senninger Irrigation, Inc., Orlando, FL.

4. ASAE. 1980. Design, installation, and performance of trickle irrigation systems. Engineering practice EP405, ASAE, St. Joseph, MI, 49085.

5. Bralts, V.F. 1983. Hydraulic design and field evaluation of drip irrigation submain units. PhD Dissertation, Michigan State University, East Lansing, MI, 310 p.

6. Bralts, V.F., I-P. Wu and H.M. Gitlin. 1981a. Manufacturing variation and drip irrigtaion uniformity. TRANSACTIONS OF THE ASAE 24(3):113-119.

7. Bralts, V.F., I-P. Wu and H.M. Gitlin. 1981b. Drip irrigation uniformity considering emitter plugging. TRANSACTIONS OF THE ASAE 24(5):1234-1240.

8. Braud, H.J. and A.M. Soom. 1981. Trickle irrigation lateral design on sloping fields. TRANSACTIONS OF THE ASAE 24(4):941-944, 950.

9. Gilad, Y., D. Peleg and G. Tirosh. 1968. Irrigation equipment tests, Report Number 81268, ICWA, Israel.

10. Howell, T.A. and E.A. HIler. 1974. Designing trickle irrigation laterals for uniformity. J. Irrig. & Drain. Div. ASCE 100(IR4):443-454.

11. Howell, T.A., D.S. Stevenson, F.K. Aljiburg, H.M. Gitlin, I-P. Wu, A.W. Warrick, and P.A.C. Raats. 1980. Chapter 16. Design and operation of trickle (drip) systems, In: M.E. Jensen (ed.) Design and operation of farm irrigation systems, ASAE Monograph No. 3, ASAE, St. Joseph, MI.

12. Law, A.M. and W.D. Kelton. 1982. Simulation modeling and analysis. McGraw-Hill, Inc., New York, NY.

13. Krameli, D., L.J. Salazar and W.R. Walker. 1978. Assessing the spatial variability of irrigation water applications. Document EPA-600/2-78-041, U.S. Environmental Protection Agency, Ada, OK.

14. Merriam, J.L. and J. Keller. 1978. Farm irrigation system evaluation: a guide for management. Utah State University, Logan, UT.

15. Nakayama, F.S. and D.A. Bucks. 1981. Emitter clogging effects on trickle irrigation uniformity. TRANSACTIONS OF THE ASAE 24(1):77-80.

16. Nakayama, F.S., D.A. Bucks and A.J. CLemmens. 1979. Assessing trickle application uniformity. TRANSACTIONS OF THE ASAE 22(3):816-821.

17. Parchomchuk, P. 1976. Temperature effects on emitter discharge rates. TRANSACTIONS OF THE ASAE 19(4):690-692.

18. Perold, R.P. 1977. Design of irrigation pipe laterals with multiple outlets. J. Irrig. & Drain. Div. ASCE 103(IR2):179-195.

19. Solomon, K. 1977. Performance comparison of different emitter types. Proc., 7th International Agricultural Plastics Congress, San Diego, CA, pp 97-102.

20. Solomon, K. 1979. Manufacturing variation of trickle emitters. TRANSACTIONS OF THE ASAE 22(5):1034-1037, 1043.

21. Solomon, K.H. 1983. Irrigation uniformity and yield theory. PhD Dissertation, Utah State University, Logan, UT. 287 p.

22. Solomon, K. and J. Keller. 1978. Trickle irrigation uniformity and efficiency. J. Irrig. & Drain. Div. ASCE 104(IR3):293-306.

23. Walpole, R.E. 1968. Introduction to Statistics. The Macmillan Company/Collier-Macmillan Ltd., London.

24. Watters, G.Z. and J. Keller. 1978. Trickle irrigation tubing hydraulics. ASAE Paper No. 78-2015, ASAE, St. Joseph, MI. 49085.

25. Wu, I-P. and H.M. Gitlin. 1974. Design of drip irrigation lines. HAES Technical Bulletin 96, University of hawaii, Honolulu, 29 p.

26. Wu, I-P. and H.M. Gitlin. 1977. Design of drip irrigation submain. J. Irrig. & Drain. Div. ASACE 103(IR2):231-243.

27. Wu, I-P. and H.M. Gitlin. 1983. Drip irrigation application efficiency and schedules. TRANSACTIONS OF THE ASAE 26(1):92-9.

28. Zur, B. and S. Tal. 1981. Emitter discharge sensitivity to pressure and temperature. J. Irrig. & Drain. Div. ASCE 107(IR1):1-9.