A Comparison of Uniformity Measures for Drip Irrigation Systems

C. R. Camp, E. J. Sadler, W. J. Busscher

Abstract. *Three drip irrigation systems were installed in 1984, two with laterals on the soil surface and one with laterals about 0.30 m below the soil surface. These systems were used to apply irrigation water and nutrients to several experiments from 1985 to 1992. Emitter plugging, system uniformity, and overall performance were evaluated for both surface and subsurface systems using several methods, and the results were compared to those obtained for unused tubing that had been saved from the original lot. Emitter uniformity values calculated for the unused laterals by the traditional and ASAE EP458 methods were similar, but differences between parameter values calculated by the two methods were greater for the used laterals, especially in the subsurface system. All uniformity values were lower for the subsurface system, primarily because of plugged emitters. Uniformity values calculated by the EP458 method (randomly selected emitters) indicate lower emitter uniformity for the used laterals in the subsurface system, but these values were not as low as those calculated using all emitters on three laterals for that system. These values indicate that the EP458 method may not always reflect true system uniformity, probably because of the small sample size and existence of completely plugged emitters. Correction of emitter flow rates for temporal pressure variation among test times improved uniformity parameter values slightly. Uniformity values predicted by design/evaluation models were similar for both surface and subsurface systems, and generally indicate better system uniformity than values calculated from emitter flow measurements. The models were unable to predict reliable uniformity values for systems because of their inability to handle emitter plugging. Based on these results, it appears that both traditional and ASAE EP458 methods can be used to evaluate drip irrigation systems, but the EP458 method generally indicates lower uniformity and should be used carefully for systems where completely plugged emitters may exist. When emitter plugging occurs, the accuracy of predictions by either method will depend primarily upon the number of emitters measured and the extent of plugging. Entry of soil particles into this eight-year-old subsurface system during construction and/or repair operations probably caused the observed emitter plugging, which emphasizes the need for exercising great care in installation and maintenance of subsurface systems if a long system life (10-15 years) is expected.* ***Keywords.** Drip/trickle/micro irrigation, Emitter flow, Uniformity coefficient, Emitter plugging, Simulation, Distribution uniformity.*

Drip irrigation can potentially provide high application efficiency and achieve high application uniformity. Both are important in producing uniformly high crop yields and preserving water quality when both water and chemicals are applied through the irrigation system. The high cost of traditional drip irrigation systems, caused by annual replacement of system components, can be substantially reduced by subsurface placement of the system (below the soil tillage zone). Subsequent use of system components for multiple years increases the amortization period, reducing annual cost. Subsurface drip irrigation offers the additional advantages of less evaporation loss and less interference with cultural operations. However, because most system components are located below the soil tillage zone, it is difficult to monitor system operation, especially reduced system performance caused by emitter plugging. Therefore, it is critical that good management practices and periodic preventive maintenance be employed to reduce emitter plugging.

To determine if water and chemicals are applied uniformly, it is necessary to evaluate emitter discharge uniformity and system performance. Application uniformity of drip irrigation systems can be expressed by several uniformity parameters; however, most require measurement of emitter discharge for a representative sample of the emitters in a system. Nakayama and Bucks (1986) reviewed several widely used parameters, including uniformity coefficient, UC, emitter flow variation, qvar, and coefficient of variation of emitter flow, CV (Christiansen, 1942; Wu et al., 1979). Solomon (1984) related expected yield to several uniformity measures, including Christiansen's uniformity coefficient, statistical uniformity (Bralts et al., 1981a,b), and distribution uniformity (Kruse, 1978). The application of statistical uniformity for evaluating drip irrigation systems in the

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field using measured emitter flow rates and pressures for randomly selected emitters and manifolds was adopted as ASAE Engineering Practice 458 (ASAE Standards, 1996). However, determination of these parameter values for field systems requires measurement of emitter flow rate and pressure at selected locations throughout the system. This can be accomplished in a straightforward manner for systems where the emitters are located on the soil surface; however, it is much more difficult for subsurface systems, where the emitters to be evaluated must be excavated to allow collection of water discharged. Additionally, Sadler et al. (1995) found that excavating the emitter increased the flow rate between 2.8% and 4.0%, but that the increased flow rate probably would not affect uniformity calculations. Models used for design and evaluation of drip irrigation systems — Energy Gradient Line (EGL), Revised Energy Gradient Line (REGL), and Step by Step (SBS) — may be useful in the evaluation of application uniformity of subsurface systems (Feng and Wu, 1990; Wu and Yue, 1991; Wu, 1992). Based on measured system uniformity for five different thin-wall tape systems in both surface and subsurface field installations, Phene et al. (1992) found that REGL or SBS models can be used to design or evaluate drip irrigation systems when emitters are not plugged.

The objectives of this research were to (1) evaluate emitter discharge uniformity for a subsurface drip irrigation system that had been used annually during the growing season for eight years; (2) compare emitter discharge uniformity of the eight-year-old subsurface system with that of unused emitters; (3) compare measured emitter uniformity values for surface and subsurface systems; and (4) compare measured emitter discharge uniformity with that computed by simulation models.

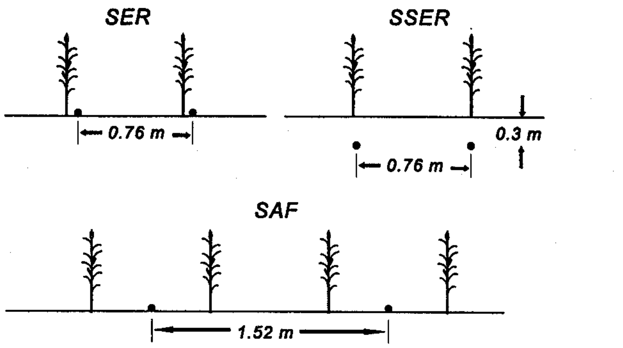

Figure 1–Schematic diagram of drip irrigation lateral placements in field systems. Systems are defined as follows: SER = surface every row, SSER = subsurface every row, and SAF = surface alternate furrow.

Materials and Methods

Field Site

Installation, 1984. Drip irrigation tubing was installed in the fall of 1984 on a 0.20-ha site of Norfolk loamy sand (Typic Kandiudult) near Florence, S.C. Prior to installing the irrigation system, the experimental site was subsoiled to a depth of 0.4 m in two directions, each diagonal to row direction, and then smoothed with a disk harrow. Thereafter, only a disk harrow and field cultivator were used to remove weeds and incorporate agricultural chemicals. The drip irrigation tubing (Drip-In, Bakersfield, Calif.) had in-line, labyrinth-type emitters spaced 0.61 m apart, each delivering 2.5 L/h at 115-kPa pressure. The experimental site included 24 plots: eight with subsurface drip irrigation and 16 with surface drip irrigation (eight for each of two lateral spacings). All plots were 12 m long and 6.1 m wide. Lateral spacing was 0.76 m for both the subsurface system and one of the surface systems and was 1.52 m for the other surface system. A schematic diagram of the three systems is included as figure 1. In most experiments conducted on this site, the laterals in the 0.76-m spacings were located adjacent to or under each crop row, and laterals in the 1.52-m spacings were located in alternate row furrows. In most experiments, there were two irrigation treatments for each lateral spacing (irrigation application modes, scheduling methods, etc.) and four replications of each treatment. Irrigation application frequency for these experiments varied from daily to weekly depending upon rainfall amount.

Laterals for the subsurface system were installed at a depth of 0.3 m using a modified subsoiler shank, and they remained in the soil thereafter. At this depth, the laterals were below the frost line and at the top of the E horizon; however, much of the E horizon had been mixed by tillage with the adjacent Ap and B horizons. The surface system was installed each year after crop emergence, was removed prior to harvest, and was stored during the off-season. The two surface spacings were considered together for the performance evaluation discussed in this article.

Modifications, 1987. Originally all laterals within a plot were connected to a single manifold, and manifolds for both the surface and subsurface systems were located on the soil surface. Within each manifold, water flow was controlled by a solenoid valve, and pressure was regulated at approximately 115 kPa. In 1987, manifolds for the subsurface system were buried at the same depth as the laterals (0.3 m). Also, two manifolds, each including individual pressure-regulating valves and vacuum breakers, were installed in each plot to allow either separate or combined control of each half plot (four laterals for 0.76-m spacing). At the same time, manifolds connecting the discharge end of each lateral (0.3 m deep) and extending to the field edge were also installed to facilitate flushing. Previously, each lateral in the subsurface system had extended to the soil surface and was terminated with a removable end cap.

Management and Operation. Crops grown on this experimental site were corn during the first three years (1985-1987) (Camp et al., 1989), spring and fall vegetables during the next two years (1988-1989; Camp et al., 1993), and corn during the next three years (1990-1992). Vegetable crops included cowpea, green bean, yellow squash, muskmelon, and broccoli. The primary irrigation water supply was a chlorinated municipal supply because of its reliability, but a marginal well was used periodically when the water flow rate and pressure was adequate for system operation. All water was passed through a 100-mesh cartridge filter, and well water was normally filtered through a sand filter first. At the beginning of and periodically during each growing season, the system was flushed by removing the end caps. At the end of each growing season, a higher-concentration chlorine solution (10-50 mg/kg available chlorine) was injected into the system, allowed to remain in the system for 1 h, and flushed with water. This treatment was applied to reduce biological activity and to retard root entry into emitters, particularly during the dormant season.

System Evaluation After Four Years. System operating parameters, including system flow rate and manifold operating pressure, were monitored during the eight-year operation period. Preliminary evaluation of the drip irrigation system had been conducted at the end of the growing season in 1989, when 16 emitters were excavated and emitter flow rates were measured. A 10-mg/kg chlorine solution was then injected into the system where it remained overnight. The next day, a 10% sulfuric acid and 100 mg/kg chlorine solution was injected into the system and again remained overnight. The system was then flushed, and flow rates were measured for the same emitters. The treatment had a small, inconsistent effect on emitter discharge rate, but did not significantly change emitter discharge uniformity.

Current Evaluation After Eight Years. The aforementioned discussion describes the history of the field systems. The status at the beginning of the current work was (1) the system was eight years old; (2) on-going monitoring had indicated that there was no major problem, but monitoring may not have been sensitive enough; and (3) a preliminary evaluation of emitter uniformity suggested there may have been some emitter plugging. The work reported here was conducted in 1993.

System Measurements

Laboratory, Every Emitter (L-EE) Test. Unused tubing from the original 1984 purchase was evaluated in the laboratory using the same pressure-regulating valves as those used in the field installation. Emitter discharge rate was determined by collecting the water discharged from every emitter on a single, 12-m length of lateral (total of 20 emitters) for a period of 5 min. This evaluation was repeated for two other laterals of the same length and material. Water volume was determined by measuring its mass using an electronic balance and then converting via density. Water flow rate, pressure, and temperature were measured for each test. Each test was conducted three times for each of the three laterals.

Field, Every Emitter (F-EE) Test. Emitter discharge rate was also determined for every emitter on each of three 12-m laterals selected randomly from both the surface and subsurface systems, all of which had been used since installation in 1984. All measurements were made while the systems operated in the normal mode. System flow rate, water pressure, and temperature were measured for each test. Emitter flow measurements for the surface system were obtained in the same manner as in the laboratory tests, and each test was conducted three times for each lateral. Emitter flow measurements for the subsurface system were obtained by excavating soil from around individual emitters and collecting the discharged water in a 500-mL container. Only one set of measurements was made for the three laterals in the subsurface system during this test.

Field, Random Emitter (F-RE) Test. For both the surface and subsurface systems, emitter discharge rate was measured for 24 randomly selected emitters that had been in use since 1984. All measurements and procedures were the same as those used in the F-EE test discussed above except that all tests were repeated three times for each lateral.

Pressure Correction. To correct for flow variations caused by temporal supply pressure variations among multiple tests for a given set of laterals, measured manifold pressures were corrected to a common value (115 kPa), the nominal pressure for all tests, using the method described by Sadler et al. (1995). Corrected flow values, q_c, were computed, using the relationship:

$$q_c = q_m \left[\frac{p_c}{p_m} \right]^{0.56} \tag{1}$$

where q_m is measured emitter flow rate, p_m is pressure measured during a test, and p_c is 115 kPa. All uniformity parameters were calculated using both measured and corrected pressure and flow values.

Uniformity Parameter Calculations

Traditional Methods. Four widely-used parameters for measuring emitter discharge uniformity are emitter q_{var}, *CV*, *UC*, and *DU*. Emitter flow rate variation, q_{var}, was calculated using the equation:

$$q_{var} = \frac{q_{max} - q_{min}}{q_{max}} \tag{2}$$

where q_{max} is the maximum emitter flow rate, and q_{min} is the minimum emitter flow rate.

Coefficient of variation, *CV*, was calculated using the equation:

$$CV = \frac{s}{\bar{q}} \tag{3}$$

where s represents the standard deviation of emitter flow rates, and $\bar{q}$ is the mean emitter flow rate.

Uniformity coefficient, *UC*, as defined by Christiansen (1942) and modified to reflect a percentage, was calculated using the equation:

$$UC = 100 \left[1 - \frac{\frac{1}{n} \sum_{i=1}^{n} | q_i - \bar{q} |}{\bar{q}} \right] \tag{4}$$

where n represents the number of emitters evaluated.

Distribution uniformity, *DU* (Kruse, 1978), was calculated using the equation:

$$DU = 100 \frac{\bar{q}_{lq}}{\bar{q}} \tag{5}$$

where $\bar{q}_{lq}$ is the mean of lowest one-fourth of emitter flow rates, and $\bar{q}$ is the mean emitter flow rate.

In tests where every emitter in the lateral (L-EE, F-EE) was evaluated, means of calculated values for each test (replication) are reported for each of the three laterals tested. Measured emitter discharge rates for all three laterals combined (60 emitters) were used to calculate parameter values for each of three tests (replications); means of calculated values are reported. In tests where 24 random emitters (F-RE) were evaluated, means of the calculated values for all tests are reported.

ASAE EP458 Method. Statistical uniformity, emitter discharge variation, hydraulic variation, and emitter performance variation were calculated using EP458 to evaluate drip irrigation systems in the field. Nomenclature used in a proposed revision of EP458 is used in this article. Confidence limits (95%) for calculated uniformity parameters were determined using the procedure in Bralts and Kesner (1983) because confidence limits were not included in EP458 for the number of system emitters tested (24). Most of the calculated uniformity values require the determination of mean emitter discharge rate, $\bar{q}$, and standard deviation, S_q, which were calculated using the equations:

$$\bar{q} = \frac{1}{n}\sum_{i=1}^{n} q_i \tag{6}$$

$$S_q = \sqrt{\frac{\sum_{i=1}^{n} q_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} q_i\right)^2}{n-1}} \tag{7}$$

The emitter discharge coefficient of variation, V_{qs}, and statistical uniformity, U_s, were calculated using the equations:

$$V_{qs} = \frac{S_q}{\bar{q}} \tag{8}$$

$$U_s = 100\,(1 - V_{qs}) \tag{9}$$

The mean hydraulic pressure, $\bar{h}$, and hydraulic design coefficient of variation, V_{hs}, were determined using equations 6, 7, and 8, respectively, with substitution of lateral line pressure, h_i, for emitter discharge, q_i, while all other variables are as previously described. The emitter discharge coefficient of variation due to hydraulics, V_{qh}, was calculated using the equation:

$$V_{qh} = xV_{hs} \tag{10}$$

where x is the emitter discharge exponent (0.54 according to manufacturer). Likewise, the statistical uniformity of emitter discharge rate due to hydraulics, U_{sh}, was calculated using the equation:

$$U_{sh} = 100\,(1 - V_{qh}) \tag{11}$$

The emitter performance variation is a measure of emitter discharge variability due to water temperature, emitter manufacturer's variation, emitter wear, and emitter plugging. The emitter performance coefficient of variation, V_{pf}, was calculated using the previously determined emitter discharge coefficient of variation, V_{qs}, the emitter discharge coefficient of variation due to hydraulics, V_{qh}, and the equation:

$$V_{pf} = \sqrt{V_{qs}^2 - V_{qh}^2} \tag{12}$$

For the case where flow was adjusted for a constant pressure, V_{hs} and V_{qh} were set equal to zero, and U_{sh} = 100; consequently, $V_{pf} = V_{qs}$.

Comparison of *UC* and U_s. Uniformity coefficient, UC, and U_s cannot be compared directly because:

$$\frac{S_q}{\bar{q}} \neq \frac{|\Delta q|}{\bar{q}} \tag{13}$$

For normally distributed data, Hart (1961) reported the relationship:

$$\frac{\sum_{i=1}^{n} |q_i - \bar{q}|}{n} = 0.798\, S_q \tag{14}$$

where S_q is as defined in equation 7. Hence, an adjusted *UC* value, UC_a, which corrects *UC* values for theoretical differences between *UC* and U_s, can be calculated from calculated U_s values. UC_a may be calculated either directly from parameters needed to calculate U_s using the relationship:

$$UC_a = 100\left[1 - 0.798\left(\frac{S_q}{\bar{q}}\right)\right] \tag{15}$$

or from U_s values using:

$$UC_a = 20.2 + 0.798\, U_s \tag{16}$$

The UC_a values were calculated using equation 16 for comparison with calculated U_s values.

Model Simulations. System dimensions and operating parameter values only were used in the computer program CEDDIS (Yue et al., 1992) to obtain application uniformity values for these models. These values were then compared with those calculated from measured emitter flow rates and lateral operating pressures. No model parameter values were calculated for emitter flow rates corrected for pressure (constant pressure).

RESULTS

FIELD SYSTEMS

In preparation for this study, we noted that pressures in several manifolds in the subsurface system exceeded the preset value. The regulating valves for these manifolds were excavated, removed from the system, and examined. Soil particles had accumulated in the pressure regulating valve and had caused the valve to malfunction, which allowed the downstream pressure to exceed the design value. After the valves were disassembled and cleaned, they operated normally. Because the color and texture of soil particles found in the malfunctioning pressure regulating valves indicated that the soil probably came from the experimental site, we believe that the soil entered the system during construction when the manifolds and pressure regulating valves were buried as part of the system modifications in 1987. Possibly, the manifolds were not flushed sufficiently before the pressure regulating valves were installed. There was no evidence that the soil particles entered the system via the water supply.

Comparison of Unused and Used Laterals

Traditional uniformity parameter values calculated for unused laterals tested in the laboratory (L-EE) and used laterals tested in the field (surface and subsurface systems) (F-EE) are shown in table 1. There was slight variation in uniformity parameter values among the three unused laterals when emitter flow rates were measured for all emitters (n = 20) on each lateral. The *CV* values were low, ranging from 0.011 to 0.018, with a mean value of 0.015. Similarly, the *UC* values were high, ranging from 98.5 to 99.1, with a mean value of 98.8. The *DU* values were slightly lower, ranging from 98.2 to 98.8, with a mean value of 98.4. Uniformity parameter values for two of three used laterals from the surface (field) system were similar to those for the unused laterals, but the third lateral had a higher *CV* value and lower *UC* and *DU* values. The *CV* values ranged from 0.017 to 0.179 with a mean value of 0.072, and *UC* values ranged from 92.4 to 98.7 with a mean value of 96.4. The *DU* values ranged from 86.1 to 97.8 with a mean value of 93.6. The degraded performance of the third lateral was caused by one partially plugged emitter.

Table 1. Uniformity parameter values calculated for various drip irrigation systems using measured flow and pressure values

System/ Evaluation Method	No. Emit- ters	No. Tests	Uniformity Parameter Values* $\bar{q}$	S_q	q_{var}	CV	UC	UC_a	DU	U_s
L-EE†, Unused, Lab			(L/h)	(L/h)	—	—	(%)	(%)	(%)	(%)
Tube 1	20	3	2.325	0.025	0.043	0.011	99.1	99.1	98.8	98.9
Tube 2	20	3	2.324	0.040	0.059	0.017	98.8	98.6	98.2	98.3
Tube 3	20	3	2.235	0.039	0.055	0.018	98.5	98.6	98.3	98.2
Mean	—	9	2.294	0.035	0.052	0.015	98.8	98.8	98.4	98.5
CBN‡	60	3	2.294	0.055	0.092	0.024	98.1	98.1	96.6	97.6
F-EE, Used, Field, Surface										
Tube 1	20	3	2.331	0.039	0.054	0.017	98.7	98.7	97.8	98.3
Tube 2	20	3	2.203	0.048	0.065	0.022	98.0	98.2	97.1	97.8
Tube 3	20	3	2.135	0.382	0.764	0.179	92.4	85.7	86.1	82.1
Mean	—	9	2.223	0.156	0.295	0.072	96.4	94.2	93.6	92.8
CBNWP‡	60	3	2.223	0.233	0.775	0.105	96.0	91.6	92.2	89.5
CBNWOP‡	59	3	2.253	0.072	0.110	0.032	97.4	97.5	96.0	96.8
F-EE, Used, Field, Subsurface										
Tube 1	20	1	2.044	0.419	0.779	0.205	88.6	83.6	78.8	79.5
Tube 2	20	1	1.620	0.960	1.000	0.592	50.1	52.7	0.2	40.8
Tube 3	20	1	1.870	0.551	1.000	0.295	82.3	76.5	65.8	70.5
Mean	—	3	1.845	0.643	0.926	0.364	73.7	70.9	48.2	63.6
CBNWP‡	60	1	1.845	0.694	1.000	0.376	74.1	70.0	50.7	62.4
CBNWOP‡	51	1	2.123	0.097	0.238	0.046	96.8	96.3	94.5	95.4
F-RE, Used, Field										
Surface	24	5	2.240	0.074	0.117	0.033	97.6	97.4	96.6	96.7
Subsurface	24	5	2.240	0.428	0.873	0.191	91.4	84.8	83.2	80.9
Models§	—	—	2.156	0.033	0.075	0.015	98.8	—	—	—

* Each value is the mean of values calculated for individual tests.

† Emitter systems are defined as L-EE = every emitter (20) on a single lateral in the laboratory, F-EE = every emitter (20) on a single lateral in the field, and F-RE = randomly selected emitters (24) from multiple laterals in a field system.

‡ Values calculated using data collected for all three tubes during a given test. Abbreviations are defined as CBNWP = combined, plugged emitters included, and CBNWOP = combined, plugged emitters (q < 1.5 L/h) omitted.

§ Values predicted by the EGL, REGL, and SBS models were equal for the surface and subsurface systems.

To determine the effect of a larger sample size on uniformity parameter values, values were also calculated from emitter measurements for all three laterals combined (n = 60 emitters) and compared with means of values calculated for each lateral separately. For both the unused laterals and the used surface laterals, the *CV* values were slightly greater and the *UC* and *DU* values were slightly lower for the combined laterals, indicating lower uniformity. This indicates both the desirability of larger sample sizes and that there is more variation among laterals than among emitters within a single lateral, especially in laterals where the uniformity is lower than for this case. When emitters with q < 1.5 L/h were omitted from uniformity calculations for the used surface system with all laterals combined (n = 59), uniformity values improved slightly (*CV* = 0.032, *UC* = 97.4, and *DU* = 96.0). Based on these measurements, it appears that slight degradation in emitter application uniformity occurred for the surface drip irrigation system during the eight-year period, but the system uniformity remained very good.

All uniformity values calculated for individual laterals in the subsurface system (F-EE) reflected lower system uniformity. One lateral had three emitters completely plugged (*CV* = 0.592, *UC* = 50.1, and *DU* = 0.2), and a second lateral had one emitter completely plugged (*CV* = 0.295, *UC* = 82.3, and *DU* = 65.8). Because two of the three laterals had plugged emitters, the mean uniformity values for the subsurface system (*CV* = 0.364, *UC* = 73.7, and *DU* = 48.2) reflected lower uniformity than for the surface system. Uniformity values calculated for all three laterals combined (n = 60 emitters) (*CV* = 0.376, *UC* = 74.1, and *DU* = 50.7) were similar to the mean values. When the emitters with q < 1.5 L/h were excluded from the calculations for all laterals combined (n = 51 emitters), uniformity values improved considerably (*CV* = 0.046, *UC* = 96.8, and *DU* = 94.5) and were similar to those for the surface system. This was probably caused by partial plugging of other emitters, which should be expected in a system where some emitters are completely plugged. Field observations indicate plugging was caused by soil particles, which were probably introduced into the system during construction and/or repair operations.

Comparison of Uniformity Evaluation Methods

Unused and Used Laterals, All Emitters (L-EE, F-EE). Emitter flow uniformity and system application uniformity parameter values calculated using the equations in EP458 are shown in table 1 for the unused and used (surface and subsurface) laterals based on measurements for every emitter on a lateral. If the assumption of normal distribution holds, direct comparison of the two methods is possible using the UC_a value for the traditional method, which accounts for theoretical differences between the two methods, and the U_s value for the EP458 method. As with the traditional parameter method, values calculated using the EP458 method indicated that the unused laterals had greater uniformity than the used (surface and subsurface) laterals; however, two of the used surface laterals were similar to the unused laterals. Values for all subsurface laterals reflected much lower uniformity, and values for one lateral (three plugged emitters) indicated very poor uniformity. Parameter values calculated for both surface and subsurface systems using emitter measurements from the three laterals combined indicated lower uniformity than the mean of values calculated for the laterals separately, but the difference was much less for the subsurface system. As expected, omitting the severely plugged emitters ($q < 1.5$ L/h) from the calculations improved uniformity values significantly. This shows the upper limit that could be expected if most plugging had been prevented. Although values were slightly different for the traditional and EP458 methods, ranges and trends were similar. The UC_a value is nearer the U_s value than is the UC value, and in some cases, accounts for about one-half the difference. While it appears that the EP458 method indicates a substantially lower uniformity value than the traditional method (using UC values) in some cases, especially when emitter plugging occurs, the difference is much less when traditional method values are calculated using the same parameters as the EP458 method (UC_a). However, significant differences in calculated values between the two methods remain, but most of the difference was removed when plugged emitters (partial and complete) were not included in parameter value calculations.

Used Laterals, Random Emitters. When used laterals in the field surface and subsurface drip irrigation systems were evaluated using traditional evaluation methods and randomly selected emitters (n = 24) (F-RE), the CV value for the surface system (0.033) was slightly greater than CV values seen above for most of the single laterals (F-EE). The CV value for the subsurface system (0.191) was greater than for the surface system, but was lower than CV values for single laterals (F-EE). The UC value for the surface system (97.6) was similar to values for the single laterals but was greater than that for the subsurface system (91.4). The UC value for the subsurface system was greater than UC values for individual subsurface laterals. The DU value for the surface system (96.6) was greater than for the subsurface system (83.2), and both were greater than the respective values for the single laterals, with the difference between subsurface systems being much greater. DU values were lowest in the F-EE subsurface system, U_s values were lowest in the F-EE surface and F-RE subsurface systems, and were almost equal in the F-RE surface system. The poorer uniformity values for the subsurface system indicate a greater degree of both partial and complete emitter plugging. Even though the UC value for the subsurface system was much less than that for the surface system, it remained good. Again, the UC_a values were more similar to the U_s values than were the UC values. DU values were generally lower than U_s and UC_a values when significant emitter plugging was included in the sample.

Evaluation results for used laterals in the field surface and subsurface drip irrigation systems using the EP458 method are shown in table 2. Mean emitter discharge rates were similar for the surface and subsurface systems, but other parameter values were quite different. Confidence limits (95%) based on calculated statistical uniformity values and the number of emitters measured are included immediately below each parameter value in table 2. The emitter discharge coefficient of variation, V_{qs}, was much less and emitter discharge statistical uniformity, U_s, was much larger for the surface system than for the subsurface system. The surface system would be evaluated 'excellent' according to EP458, while the subsurface system would be evaluated between 'good' and 'fair'. The emitter discharge coefficient of variation due to hydraulics, V_{qh}, value for the surface system (0.019) was half the value for the subsurface system (0.038), indicating less difference between the two systems for this parameter. Likewise, the statistical uniformity of emitter discharge rate due to hydraulics, U_{sh}, indicates less difference between the two systems and comparable hydraulic design characteristics. Finally, the emitter performance coefficient of variation value, V_{pf}, indicates that the surface system is significantly more uniform than the subsurface system (0.027 vs 0.187). Because the U_{sh} (hydraulic design) values indicated that the surface and subsurface systems were comparable, the difference in V_{pf} values for the two systems indicates the difference was caused by factors other than hydraulic design characteristics (e.g., emitter plugging).

Table 2. Evaluation of emitter uniformity using randomly selected emitters (RE) in field systems, the ASAE EP458 method for calculating parameter values, and measured flow and pressure values

Field Drip Irrigation System	Uniformity Parameter Values* (ASAE EP458)						
	$\bar{q}$ (L/h)	S_q (L/h)	V_{qs} —	U_s (%)	V_{qh} —	U_{sh} (%)	V_{pf} —
Surface	2.240	0.074	0.033	96.7	0.019	98.1	0.027
Conf. limit†	—	—	±0.010	±0.990	±0.006	±0.994	±0.008
Subsurface	2.240	0.428	0.191	80.9	0.038	96.2	0.187
Conf. limit†	—	—	±0.059	±0.941	±0.011	±0.989	±0.058

* Each value is the mean of values calculated for five individual tests (replications).

† Confidence limits (95%) appropriate for statistical uniformity values and evaluation of 24 system emitters based on ASAE EP458 and Bralts and Kesner (1983).

Uniformity parameters calculated using the EP458 method (F-RE) indicate better system uniformity than values calculated using the traditional methods and EP458 parameters for measurements from all emitters on a lateral (F-EE). These EP458 parameter values (F-EE) are outside the calculated confidence limits of the values calculated using the EP458 method for random emitter measurements (F-RE). This difference probably occurred because the plugged emitters were not selected in the relatively small, random sample used in the EP458 method. When using the EP458 method, one should be aware of the restrictions and limitations that are inherent in using the method and realize that the method may not always estimate true system uniformity because of limited sample size and existence, though perhaps unknown, of completely plugged emitters.

Although limitations are not explicitly stated in the EP458 method, the inclusion of plugged emitters in the sample for determining the field U_s has been discouraged (Bralts et al., 1987). The rationale for this is that development of EP458 assumes a normal distribution of data, but the presence of fully plugged emitters results in a bimodal distribution, which results in coefficient of variation values outside the normal confidence limits. If this is the case, a statement of limitations or conditions under which the method may be reliably used should be added to EP458.

Effect of Flow Correction for Pressure Variation on Parameter Values. All parameter values were calculated using flow rates corrected for temporal pressure variations among the various test times that were caused by variation in water supply pressure. Parameter values for the L-EE, F-EE, and F-RE systems using pressure-corrected flow values are shown in table 3. Parameter values for the L-EE system were similar for both the measured (table 1) and corrected flow rates because the water supply pressure variation was less for this test. The values for corrected flow rates in the F-EE system, both for surface and subsurface laterals, were similar or slightly better than those for measured flow rates, and the difference was greater when plugged emitters were not included in parameter calculations. In the F-RE system, parameter values were only slightly better for the corrected flow rates.

Parameter values calculated using the ASAE EP458 method, random emitters (n = 24), and corrected flow values are shown in table 4. Again, the uniformity parameter values for the corrected flow rates were slightly better than those for measured values (table 2). The values for V_{pf} changed little because the direct effect of pressure variation was removed (V_{qh} = 0 and U_{sh} = 100). The overall adjective classifications (excellent, good, fair, etc.) for the systems based on ASAE EP458 did not change with correction of flow rate for pressure variation, although numerical values increased slightly.

Model Simulations. Parameter values predicted by the EGL, REGL, and SBS models for the surface and subsurface systems were equal, both among models and for the two systems; consequently, single values are reported for each parameter in table 1. Equality of parameter values among models and systems is not surprising because these systems are small in size with little change in elevation when compared to most field systems, and hydraulic design is not a major consideration. For similar reasons, no model parameter values were calculated for the flow rates corrected for constant pressure (table 3). Calculated parameter values (based on measured flow rates) for the surface system were very similar to those predicted by the models, but those for the subsurface system indicated lower uniformity, probably because of emitter plugging. All model values were determined with model emitter plugging input values set to zero. When non-zero plugging input values were used, even very small values, model predictions were erratic. Consequently, we concluded that the models could be used only when plugging is not a factor in system evaluation, which is similar to the conclusion reached by Phene et al. (1992).

Table 3. Uniformity parameter values calculated for various drip irrigation systems using corrected flow and pressure values

System/ Evaluation Method	No. Emit-ters	No. Tests	Uniformity Parameter Values* $\bar{q}$	S_q	q_{var}	CV	UC	UC_a	DU	U_s
L-EE†, Unused, Lab			(L/h)	(L/h)	—	—	(%)	(%)	(%)	(%)
Tube 1	20	3	2.387	0.026	0.043	0.011	99.1	99.1	98.8	98.9
Tube 2	20	3	2.387	0.041	0.059	0.017	98.8	98.6	98.2	98.3
Tube 3	20	3	2.294	0.040	0.055	0.018	98.5	98.6	98.3	98.2
Mean	—	9	2.356	0.036	0.052	0.015	98.8	98.8	98.4	98.5
CBN‡	60	3	2.356	0.057	0.092	0.024	98.1	98.1	98.6	97.6
F-EE, Used, Field, Surface										
Tube 1	20	3	2.265	0.037	0.054	0.017	98.7	98.7	97.8	98.3
Tube 2	20	3	2.269	0.050	0.065	0.022	98.0	98.2	97.1	97.8
Tube 3	20	3	2.178	0.389	0.764	0.179	92.4	85.7	86.1	82.1
Mean	—	9	2.237	0.159	0.295	0.072	96.4	94.2	93.6	92.8
CBNWP‡	60	3	2.237	0.226	0.766	0.101	96.8	91.9	93.7	89.9
CBNWOP‡	59	3	2.266	0.043	0.069	0.019	98.4	98.5	97.5	98.1
F-EE, Used, Field, Subsurface										
Tube 1	20	1	2.117	0.434	0.779	0.205	88.6	83.6	78.8	79.5
Tube 2	20	1	1.695	1.004	1.000	0.592	50.1	52.7	0.2	40.8
Tube 3	20	1	2.041	0.602	1.000	0.295	82.3	76.5	65.8	70.5
Mean	—	3	1.951	0.680	0.926	0.364	73.7	70.9	48.2	63.6
CBNWP‡	60	1	1.951	0.732	1.000	0.375	74.2	70.1	51.3	62.5
CBNWOP‡	51	1	2.246	0.083	0.203	0.037	97.5	97.0	95.4	96.3
F-RE, Used, Field										
Surface	24	5	2.262	0.067	0.101	0.029	97.7	97.7	96.5	97.1
Subsurface	24	5	2.247	0.419	0.862	0.186	92.1	85.1	84.8	81.4

* Each value is the mean of values calculated for individual tests.

† Emitter systems are defined as L-EE = every emitter (20) on a single lateral in the laboratory, F-EE = every emitter (20) on a single lateral in the field, and F-RE = randomly selected emitters (24) from multiple laterals in a field system.

‡ Values calculated using data collected for all three tubes during a given test. Abbreviations are defined as CBNWP = combined, plugged emitters included, and CBNWOP = combined, plugged emitters (q < 1.5 L/h) omitted.

Table 4. Evaluation of emitter uniformity using randomly selected emitters (RE) in field systems, the ASAE EP458 method for calculating parameter values, and corrected flow and pressure values

Field Drip Irrigation System	Uniformity Parameter Values* (ASAE EP458) $\bar{q}$ (L/h)	S_q (L/h)	V_{qs} —	U_s (%)	V_{qh} —	U_{sh} (%)	V_{pf} —
Surface	2.262	0.067	0.029	97.1	0	100	0.029
Conf. limit†	—	—	±0.010	±0.990	—	—	—
Subsurface	2.247	0.419	0.186	81.4	0	100	0.186
Conf. limit†	—	—	±0.057	±0.943	—	—	—

* Each value is the mean of values calculated for five individual tests (replications).

† Confidence limits (95%) appropriate for statistical uniformity values and evaluation of 24 system emitters based on ASAE EP458 and Bralts and Kesner (1983).

SUMMARY AND CONCLUSIONS

Drip irrigation laterals that had been used since 1984 in both surface and subsurface systems were evaluated using both traditional emitter discharge uniformity parameters and a method included in ASAE EP458. These values were compared to those measured for unused laterals that had been saved from the original lot and to values predicted by three design models. Emitter uniformity values calculated by the traditional and EP458 methods were similar for the unused laterals (L-EE), but differences were greater for the used laterals in the field systems (F-EE), especially in the subsurface system. Traditional uniformity values were lower for the subsurface system than for the surface system, primarily because four emitters among three laterals were completely plugged. Correction of emitter flow rate for temporal water supply variation among various test times slightly improved uniformity parameter values. Uniformity values calculated by the EP458 method (random emitters) indicate lower emitter uniformity for the used laterals from the subsurface system in the field, but not as low as those calculated using all emitters on three laterals. The calculated values using all emitters were well outside the confidence limits for values calculated using the EP458 method, indicating that the EP458 method may not always reflect true system uniformity. The EGL, REGL, and SBS models predicted the same uniformity parameter values for surface and subsurface systems, and all values indicated greater uniformity than did the values based on measured values. However, this was expected because the models could not handle non-zero emitter plugging inputs.

Based on these evaluations, it appears that both the traditional methods and those described in EP458 can be used to evaluate drip irrigation systems. Overall procedures and guidance are provided in EP458, but the procedure remains somewhat complex and basic assumptions and limitations are not explicitly indicated. The surface system that had been used for at least eight years retained excellent uniformity, and measured emitter uniformity values were generally comparable to those of unused tubing of the same age. Measured emitter discharge uniformity for the subsurface system was somewhat less and rated between 'good' and 'fair,' based on guidelines in EP458. Emitter discharge uniformity values based on measurements for every emitter on three laterals in the subsurface system (F-EE) indicate much poorer system uniformity than other methods and values, indicating the value of a larger sample size when making uniformity evaluation measurements. Soil particles that were suspected to have entered the system while modifications were being installed probably caused the observed plugging. This emphasizes the need for exercising great care in system installation and maintenance of subsurface systems if a useful life of 10 to 15 years is expected.

REFERENCES

ASAE Standards, 43rd Ed. 1996. EP458. Field evaluation of microirrigation systems. St. Joseph, Mich.: ASAE.

Bralts, V. F., I. Wu and H. M. Gitlin. 1981a. Manufacturing variation in drip irrigation uniformity. *Transactions of the ASAE* 24(1):113-119.

Bralts, V. F., I. Wu and H. M. Gitlin. 1981b. Drip irrigation uniformity considering emitter plugging. *Transactions of the ASAE* 24(5):1234-1240.

Bralts, V. F. and C. D. Kesner. 1983. Drip irrigation field uniformity estimation. *Transactions of the ASAE* 26(5):1369-1374.

Bralts, V. F., D. M. Edwards and I-Pai Wu. 1987. Drip irrigation design and evaluation based on the statistical uniformity concept. In *Adv. in Agron.* 4:67-117.

Camp, C. R., E. J. Sadler and W. J. Busscher. 1989. Subsurface and alternate-middle micro irrigation for the southeastern Coastal Plain. *Transactions of the ASAE* 32(2):451-456.

Camp, C. R., J. T. Garrett, E. J. Sadler and W. J. Busscher. 1993. Microirrigation management for double-cropped vegetables in a humid area. *Transactions of the ASAE* 36(6):1639-1644.

Christiansen, J. E. 1942. Hydraulics of sprinkling systems for irrigation. *Trans. Amer. Soc. Civ. Eng.* 107:221-239.

Feng, J. and I. P. Wu. 1990. A simple computerized drip irrigation design. In *Proc. 3rd Nat. Irrig. Symp.*, 348-353. ASAE Publ. No. 04-90. St. Joseph, Mich.: ASAE.

Hart, W. E. 1961. Overhead irrigation pattern parameters. *Agricultural Engineering* 42(7):354-355.

Kruse, E. G. 1978. Describing irrigation efficiency and uniformity. *J. Irrig. Drain. Div. ASCE* 104(IR):35-41.

Nakayama, F. S. and D. A. Bucks. 1986. *Trickle Irrigation for Crop Production — Design, Operation and Management*, Developments in Agricultural Engineering 9. New York, N.Y.: Elsevier.

Phene, C. J., R. Yue, I. Wu, J. E. Ayars, R. A. Schoneman and B. Meso. 1992. Distribution uniformity of subsurface drip irrigation systems. ASAE Paper No. 92-2569. St. Joseph, Mich.: ASAE.

Sadler, E. J., C. R. Camp and W. J. Busscher. 1995. Emitter flow rate changes caused by excavating subsurface microirrigation tubing. In *Proc. 5th Int. Microirrigation Cong.*, 763-768. St. Joseph, Mich.: ASAE.

Solomon, K. H. 1984. Yield related interpretations of irrigation uniformity and efficiency measures. *Irrig. Sci.* 5:161-172.

Wu, I. P. 1992. Energy gradient line approach for direct calculation in drip irrigation design. *Irrig. Sci.* 13:21-29.

Wu, I. P., T. A. Howell and E. A. Hiler. 1979. Hydraulic design of drip irrigation systems. Hawaii Agric. Exp. Sta. Tech. Bull. 105. Honolulu, Hawaii: Univ. of Hawaii.

Wu, I. P. and R. Yue. 1991. Drip irrigation design using energy gradient line approach. ASAE Paper No. 91-2154. St. Joseph, Mich.: ASAE.

Yue, R., C. J. Phene, F. Dale, J. E. Ayars, R. A. Schoneman, B. Meso and I. P. Wu. 1992. Field uniformity of subsurface drip irrigation. In *Proc. Conf. on Subsurface Drip Irrigation, Theory, Practices and Applications*, 183-185, Coalinga, Calif., Pub. No. 921001. Fresno, Calif.: California State University.