Management, Maintenance, and Water Quality Effects on the Long-term Performance of Subsurface Drip Irrigation Systems

J. Enciso-Medina, W. L. Multer, F. R. Lamm

Abstract. *The longevity of subsurface drip irrigation (SDI) systems is a key factor in the profitability of these systems when used for lower-value commodity crops (typically the fiber and grain crops). The system management and maintenance protocols, as well as the source water quality, can greatly impact the longevity of these systems. This study evaluated 10 subsurface drip irrigation systems in 2008 and 8 additional systems in 2009 that had been in operation between 6 and 20 years. System uniformity was evaluated by the uniformity parameters, emitter discharge variation, q_{var}, and the lower quartile distribution uniformity of emitter discharge, DU_{lq}. Pressure measurements along the dripline also were used to determine if q_{var} was primarily explained by friction losses. Two-thirds of the evaluated SDI systems had q_{var} less than 20% and DU_{lq} greater than 80 which would be acceptable and one-third of the systems had q_{var} less than 10% and DU_{lq} greater than 90 which would be good to excellent uniformity. There was very little correlation in system uniformity and system life with the oldest system (20 years) having the greatest uniformity. Uniformity problems on nearly two-thirds of the systems appeared to have been exacerbated by incorrect operating pressure (both too low and too high) with the six best performing systems operating between 65% and 100% of the manufacturer's specified nominal operating pressure. Water hardness and total dissolved salts were the major water quality concerns. Poor maintenance (e.g., no or infrequent chlorination; inadequate filtration system backflushing) appeared to reduce uniformity in between one-third and one-half of the systems. The producer's lack of installation records and operator's guides likely negatively impacted system uniformity through these poor management and maintenance procedures. The use of both q_{var} and DU_{lq} to evaluate performance of SDI systems appeared to enhance the determination of the primary causes of SDI system nonuniformity.*

Keywords. *Distribution uniformity, Emitter discharge variation, Microirrigation, Subsurface drip irrigation.*

Subsurface drip irrigation (SDI) systems are very uniform when properly designed, installed, and operated; distribution uniformities greater than 90% can be obtained with these systems (Camp, 1998). The superior uniformity of these systems make it possible to apply fertilizers and chemicals through the water in small and frequent quantities, increasing water application, and nutrient utilization efficiencies (Lamm and Camp, 2007). Subsurface drip irrigation (SDI) systems are preferably used over alternative systems for vegetable crop production in southern Texas because the large initial SDI system costs can be offset by crop profits. If the longevity of the SDI systems can be increased through properly designed and maintained systems, these systems could be economically justified for other row crops. In some regions, SDI systems have been used for lower-value commodity crop production such as in Kansas for irrigating corn and West Texas to irrigate cotton (Enciso et al., 2002; Lamm and Trooien, 2003). Cotton producers have replaced furrow irrigation systems with SDI systems to spread limited water resources for the declining aquifers of West Texas and also to remain profitable. Several cotton producers noted an average 27% increase in yield with SDI systems over surface (furrow) irrigation, with yield increases 2.5 times greater than dryland (Henggeler et al., 1994).

The use of SDI systems in row crops may also be influenced by the initial cost of the system. The cost of an SDI system will depend on the dripline spacing or the row configuration (Enciso et al., 2002). The cost percentages by irrigation components for a 1.02-m dripline spacing are approximately: pump and filters 14%, dripline 38%, PVC pipe 25%, installation 15%, and fertilizer injectors and accessories 8% (Frerich, 2004). The dripline represents the greatest cost of the system and its longevity can greatly impact the system's annual amortized cost. Economic comparisons of SDI systems and center pivot sprinkler irrigation systems (CP) for corn production in Kansas have indicated that SDI systems must last at least 10 to 15 years to approach economic competitiveness with CP systems (Lamm et al., 2011). Successful maintenance programs can help prevent emitter clogging and increase the longevity of the system. Emitter clogging can be produced by physical, chemical, and biological causes (Bucks et al., 1979).

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Physical clogging is caused by suspended inorganic particles (such as sand, silt, clay, plastic fragments from the installation process), organic materials (spiders, ants, snails, etc.), and microbiological debris (algae and protozoa). Boman (1995) determined that 46% of the clogging of microsprinklers was due to algae, 34% from ants and spiders, 16% from snails, and 4% from physical particles such as sand and fragments of PVC. Boman also found that the clogging rate was inversely related to the orifice area of the emitters. Filtering of the water and flushing of manifolds and driplines are simple and necessary procedures that can help to prevent or reduce physical clogging (Nakayama and Bucks, 1991). Filtration can help prevent inorganic particles and organic materials suspended in water, and precipitates formed during chemical injection from entering the SDI system. Flushing driplines and manifolds removes the inorganic and organic materials deposited on the inside wall of driplines from the system, thus helping to reduce clogging (Puig-Bargués et al., 2010a and 2010b). Chlorine injections, greater emitter orifice area, and a built-in filtration area for the emitters can reduce biological emitter clogging produced by algae and protozoa (Dehghanisanij et al., 2005). Another biological clogging problem can be produced by root intrusion into the emitters especially in Bermuda grass irrigation, or in vines and trees, which is commonly controlled by injections of trifluralin (Choi and Suarez Rey, 2004; Burt and Styles, 2007).

The chemical composition and pH of the water source and the water's interaction with chemicals added during chemigation can have a very significant influence on the level of emitter clogging. Emitter clogging criteria were proposed by Bucks et al. (1979) for emission devices with discharges ranging from 2 to 8 L/h. The primary water characteristics that can affect chemical clogging are: pH, salts, bicarbonates, manganese, total iron, and hydrogen sulfide (Enciso et al., 2004; Rogers et al., 2003). Even phosphoric acid, which is often injected in microirrigation system water to prevent chemical clogging, can result in phosphate precipitants with the calcium and magnesium when the injection rate is too low allowing too much dilution of the acid (i.e., pH rises with dilution). For high pH waters, it is advisable to consider mixing the phosphoric acid with urea-sulfuric-acid (e.g., N-pHuric 15/49) prior to injection to help ensure the water pH will remain at 3.0 or lower (Burt et al., 1995). Chlorine (e.g., sodium hypochlorite) and acid (e.g., sulfuric acid) chemical injections are often needed to avoid emitter clogging caused by bacterial growth, algae, iron and manganese oxides and sulfides, calcium and magnesium precipitation, and root intrusion (Burt and Styles, 2007).

Microirrigation has been used with a variety of water sources such as ground water, surface water, or treated effluent. Secondary municipal effluent has been successfully used with surface drip irrigation by using sand media filtration and injecting continuous chlorination to a free chlorine residue concentration of 0.4 mg/L without reducing emitter discharge (Hills and Brenes, 2001). Beef lagoon effluent has also been used successfully with manageable clogging problems (Trooien, et al., 2000) with smaller emitters typically used for freshwater applications perhaps too risky for use with effluent even with disk filtration to 55 μm (200 mesh). In a later report of the same study, Lamm et al. (2002) found the discharge rates of the two smallest emitter sizes (0.6 and 0.9 L/h-emitter) decreased approximately 40% and 30%, respectively, during the four seasons, indicating considerable emitter clogging. The three driplines with the greatest discharge rate emitters (0.1.5, 2.3, and 3.5 L/h) only had approximately 7%, 8%, and 13% emitter discharge reductions, respectively. Sewage water clogged 26% more emitters than groundwater (Li et al., 2009) in a study in China. They also found that with pressure compensating emitters that the clogging distribution occurred randomly along the dripline, but the clogging of non-pressure compensating emitters tended to occur at the distal end of the driplines. Clogging of drip emitters can be also affected by the type of emitter (de Kreij et al., 2003; Liu and Huang, 2009). It has been observed that on-line pressure compensating emitters have better anti-clogging properties than in-line emitters. The on-line emitters are when the dripline is punched and the emitters are inserted into the line and the in-line emitters are when the emitters are extruded into the dripline. It has also been observed that turbulent-flow emitters have better anti-clogging properties than laminar-flow emitters (de Kreij et al., 2003; Liu and Huang, 2009). Most of the reported clogging studies have been conducted in controlled field experiments with duration of less than 4 years. More studies which document the performance of older SDI systems that are still currently operational are needed. It is also important to document how these systems have been affected by the source water quality, what management and maintenance practices have been adopted, and whether the longevity of operation has affected system performance and irrigation uniformity. Considering the large investment needed for SDI, it is vital to extend their lifetime with proper design, management, and maintenance practices. The main objective of this study was to evaluate the uniformity of existing SDI systems in West Texas with a life greater than seven years and determine if design, management, and maintenance practices have affected uniformity.

Procedures

Study Location and SDI System Selection Procedures

The study was conducted in an area located near St. Lawrence, Texas. The region is semi-arid and receives less than 400 mm of rainfall annually. The main water sources are from one of several aquifers such as the Edwards Trinity Plateau, the Ogallala, and the Cenozoic Pecos Alluvium.

Ten farms were selected in 2008 and eight in 2009 to evaluate the SDI system performance and to evaluate the maintenance program in the resultant system performance and longevity. The 2008 sites were chosen by trying to find older, operational systems somewhat randomly scattered within a three county area (Reagan, Upton, and Glasscock counties). As with any study conducted on producer fields, the extent of randomness was influenced somewhat by the requirement of finding willing producers. During the second year, the systems were also selected based on how old they were, as well as for their suspected clogging problems. Overall, the results may not be a true representation of the distribution of older SDI systems with a given level of performance, but rather a sampling and discussion of some of the issues facing older SDI systems.

Sampling Procedures for Hydraulic Performance

Hydraulic characteristics of the SDI systems, such as the nominal emitter pressure and discharge, and emitter spacing were obtained from the producer or the installer. In most cases, producers had not been given or no longer possessed any detailed descriptions of their system installation and design. Emitter discharge and pressure was measured at 18 selected locations within a single zone of each SDI system with the exception of System J. This system had two zones with 183-m driplines being irrigated on alternate sides of the centerline of the 366-m field. In the system evaluation for this field, 9 measurements from each zone were obtained instead of 18. The results from the two zones of System J were averaged. Six driplines, evenly spaced across the width of the zone were selected for sampling. Along each of the six driplines, three measurements were made, near the inlet and distal ends (approximately 8-9 m from ends) and near the center of the dripline length. The measurements were made by carefully excavating the soil by hand, trying to avoid damaging the dripline, to a depth of approximately 5 cm below the emitter to allow for the small water collection containers (40-mL capacity). Water dripping from each sampled emitter was collected for a period of 120 s as measured by a stop watch. Occasionally, for some emitters with less discharge, the time was extended to 180 to 300 s to increase the accuracy of the emitter discharge calculations. Experimental error was further reduced by collecting and averaging three water collection samples for each of the 18 selected emitters. Emitter discharge was calculated as the average sample catch volume divided by sample time. The dripline pressure at each sampling location was determined using a glycerin-filled pressure gauge (±1.5% of full scale, 0 to 207 kPa). A syringe, connected to the pressure gauge with plastic tubing, was used to pierce the dripline, providing a non-leaking interference fit. After using the syringe to measure the dripline pressure, a small plastic plug (known as a goof plug), also providing an interference fit, was inserted into the hole of the dripline as a permanent repair of the leak. Sadler et al. (1995) reported the excavation process itself can affect the emitter discharge with increases of as much as 4% due to removal of overburden on some soil types. However, these differences in emitter discharge are still small and in the case of this study the emitter discharges are being compared against each other (i.e., all sampled emitters are being excavated) so the effect is less important.

The emitter discharge data was used to calculate the emitter discharge variation and the Lower Quartile Distribution Uniformity (DU_{lq}). The pressure data was used to calculate the pressure variation and the amount of emitter discharge variation attributable to changes in pressure. The emitter discharge variation and pressure variation are calculated as:

$$X_{var} = 100\left[\frac{X_{max} - X_{min}}{X_{max}}\right] \quad (1)$$

where the average inlet and average outlet pressures (P_{max} and P_{min} in any acceptable but consistent units) and the average inlet and average outlet emitter discharges (q_{max} and q_{min} in any acceptable but consistent units) are substituted for the maximum and minimum X values for the pressure and emitter discharge variations (P_{var} and q_{var}), respectively. These inlet and outlet values were used instead of the absolute maximum and minimum values in this study, so that the pressure and emitter discharge variations could be examined with respect to friction losses along the length of the dripline. A problem that occurs with using the absolute values is that a fully clogged emitter with no discharge greatly increase the calculated q_{var} and greatly bias any conclusions about what portion of the variation was caused by hydraulic design (i.e., friction losses). Emitter discharge variation between 0 and 10% is generally considered desirable, between 10% and 20% is considered acceptable, and greater than 20% is considered unacceptable (Clark et al., 2007). The averaging of the six measurements from driplines at each of the three distances from the dripline inlet improves the determination of q_{var} with respect to the hydraulic design. However, it should be noted that using absolute maximum and minimum values in the q_{var} calculations is sometimes useful when trying to highlight problems caused by random clogging (minimum values) or emitter wear (maximum values). In this study, the aspect of random emitter clogging is covered to a greater extent by the calculation of DU_{lq}.

The Lower Quartile Distribution Uniformity is calculated as:

$$DU_{lq} = 100\left[\frac{q_{lq}}{\bar{q}}\right] \quad (2)$$

where q_{lq} is the average emitter discharge from the lower quartile of sampled emitters and $\bar{q}$ is the mean emitter discharge for all of the emitters.

The emitter discharge, q in L/h, can also be expressed using the emitter discharge function:

$$q = kP^X \quad (3)$$

where k is the emitter discharge coefficient that accounts for emitter design and unit conversion, P is the dripline pressure at the emitter in kPa, and x is the emitter exponent that can be determined from testing and is typically provided by the manufacturer. The emitter discharge variation attributable to changes in pressure, q_{pvar} , can be calculated by substitution of the right side of equation 3 for the q terms in the calculation of equation 1 as:

$$q_{pvar} = 100\left[\frac{P_{max}^X - P_{min}^X}{P_{max}^X}\right] \quad (4)$$

where all terms have been previously defined in the preceding paragraphs. A direct comparison of q_{var} and q_{pvar} allows inferences about whether SDI system nonuniformity is being caused by design and/or operational hydraulic factors or that nonuniformity is being caused by other factors (e.g., emitter clogging due to poor water quality and /or maintenance). In this study, SDI systems were considered to have their emitter discharge variation explained by the pressure variation when an arbitrary difference in q_{var} - q_{pvar} was negative or less than a positive value of 5%.

Water Quality Sampling and Analysis

The irrigation water was evaluated for 7 of the 10 sites in 2008 and for all 8 sites in 2009. During the hydraulic evaluation, an approximately 1-L water sample was collected from the well before it passed through the filtration system. The water samples were sent for water quality analysis by the Soil, Water and Forage Testing Laboratory, which is housed in the Department of Soil and Crop Sciences and is part of the Texas AgriLife Extension Service, an agency within the Texas A&M University System.

SDI System Management and Maintenance Characteristics

The SDI system, management, and maintenance characteristics were collected by a student who visited each producer in person (table 1). As stated earlier, most producers did not have detailed records of their system. Emitter exponents were obtained from the manufacturer's specifications.

All of the SDI systems had sand media filtration with the exception of site M which used disk filtration. All of the filtration systems used automatic backflushing which were set at a fixed time interval and also set by a fixed filter inlet/outlet pressure differential. The filter backflushing interval was generally a fixed time determined by the producer from observations about how rapidly the filters loaded up. In addition to this manual setting of the backflush interval, an automatic backflushing was set to occur when the pressure differential between the inlet and outlet of the filter exceeded approximately 48 kPa. The filters have the operating rule that when the pressure differential reaches the preset critical value, a switch will override the manual preset time setting and initiate a backflush cycle. A flush cycle initiated by the pressure differential switch is treated like a regular backflush cycle and will zero the elapsed interval time so that the correct interval time setting will initiate the next backflush cycle. Producers generally reported that pressure differential was never reached because their water was relatively clean.

Results and Discussion

Characteristics of the Source Water and Fertigation Pracatices

The irrigation water was generally good quality water pumped primarily from the Edwards Trinity Plateau and Ogallala aquifers with only small amounts of sodium salinity (table 2). Site C had the greatest salinity from the 2008 samples with 2352 mg/L of total dissolved solids (TDS). Site K had the greatest salinity of the 2009 samples with 3541 mg/L of total dissolved solids (TDS). The water is considered to have a very high salinity hazard when it is above 2250 dS/m (1575 mg/L) according to the classification by the U.S. Salinity Laboratory (Cuenca, 1989). Successful use of highly saline waters for irrigation requires salt-tolerant plants, good soil water drainage, extra irrigation application for leaching, and/or periodic utilization of low-salinity water. Cotton has a relatively high salinity tolerance and has generally been grown successfully using the irrigation waters of this region.

The Sodium Adsorption Ratio (SAR) is a measure of the sodium concentration in relation to the calcium and magnesium charge in concentrations in meq/L. Site K had the greatest SAR at 4.8 (table 2). Waters with an SAR less than 10 do not typically represent a sodium hazard.

Bicarbonate concentrations exceeding about 122 mg/L and pH exceeding about 7.5 can cause calcium carbonate precipitation. All of the systems had bicarbonate concentrations exceeding that level and three of the systems had pH of 7.5 or greater (table 2). System K had the lowest pH at 7.1. Water hardness is expressed as the combination of calcium and magnesium in mg/L. All of the sites had values of the combined calcium and magnesium are over 100 mg/L and special precautions are necessary if phosphoric acid is to be injected into the system. The water should be acidified before phosphoric acid is injected to avoid the formation of

Table 1. System characteristics[a] of the 18 SDI systems evaluated in West Texas in 2008 and 2009.

Site	Years Since Installation	Dripline Brand and Model Name	Dripline Inside Diameter (mm)	Emitter Spacing (cm)	Nominal Emitter Discharge (L/h)	Nominal Dripline Pressure (kPa)	Emitter Exponent	Dripline Length (m)	Filtration System Type
A	12	Netafim Python	22	76	1.51	81	0.45	381	Sand media
B	11	Netafim Python	22	60	0.76	81	0.45	384	Sand media
C	10	Netafim Python	22	60	0.91	81	0.45	488	Sand media
D	11	Netafim Python	22	60	0.61	81	0.45	337	Sand media
E	8	Netafim Python	22	60	0.76	81	0.45	367	Sand media
F	10	Netafim Python	22	60	0.61	81	0.45	379	Sand media
G	9	Netafim Python	22	60	0.76	81	0.45	518	Sand media
H	15	Netafim Python	20	76	1.51	81	0.45	396	Sand media
I	15	Netafim Python	20	76	1.51	81	0.45	386	Sand media
J	20	Chapin Twinwall IV	16	30	0.57	69	0.53	183	Sand media
K	9	Netafim Python	22	76	0.87	81	0.45	549	Sand media
L	9	Netafim Python	22	76	0.87	81	0.45	618	Sand media
M	10	Netafim Python	22	76	0.87	81	0.45	447	Grooved disk
N	9	Netafim Python	22	76	0.67	81	0.45	521	Sand media
O	6	Netafim Python	25	60	0.61	81	0.45	619	Sand media
P	10	Netafim Python	22	60	0.87	81	0.45	401	Sand media
Q	10	Netafim Python	22	76	0.87	81	0.45	543	Sand media
R	12	Netafim Python	22	76	0.87	81	0.45	422	Sand media

[a] System characteristics as provided by the producers and/or the dealers. Emitter exponents were obtained from the manufacturer's specifications.

Table 2. Water quality parameters for the SDI system that were evaluated in West Texas in 2009 and 2009.

Parameter	2008 Sites[a]							2009 Sites							
	A	B	C	D	E	F	G	K	L	M	N	O	P	Q	R
Calcium (Ca) (mg/L)	104	129	235	151	101	112	96	526	95	91	184	214	116	87	91
Magnesium (Mg) (mg/L)	36	41	119	61	39	23	32	105	27	38	60	59	26	26	27
Boron (B) (mg/L)	0.80	1.05	1.34	1.26	0.70	0.49	0.79	1.39	0.51	0.63	1.01	0.84	0.57	0.49	0.53
Bicarbonate (HCO_3) (mg/L)	269	260	238	245	262	279	269	183	265	258	234	208	258	291	252
Chloride (Cl^-) (mg/L)	95	133	274	190	90	105	102	517	81	96	174	119	99	94	70
pH	7.30	7.30	7.20	7.30	7.40	7.30	7.30	7.10	7.51	7.48	7.28	7.32	7.35	7.62	7.50
Conductivity (dS/m)	1,223	1,423	2,890	1,807	1,148	960	1,146	4,100	990	1,077	1,775	1,674	2,120	1,130	890
Total Dissolved Salts (TDS) (mg/L)	944	1,081	2,352	1,443	929	750	889	3,541	820	871	1,485	1,453	1,357	840	744
SAR	2.8	3.0	4.4	3.5	2.5	1.8	2.9	4.8	2.2	2.3	2.7	2.0	2.7	2.6	1.8
Iron (Fe) (mg/L)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Manganese (Mn) (mg/L)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

[a] Parameter data for systems H, I, and J from 2008 was not available.

phosphates that could precipitate in the dripline and clog its emitters. The injection of fertilizers containing phosphorus will likely be a problem if proper precautions are not taken. Many of the producers did apply phosphorus fertilizers or phosphoric acid through their SDI systems (table 3), but it is unknown what clogging precautions the producers may have taken or even have been aware of. The producers used UAN 32-0-0 as their nitrogen source for fertigation (table 3) which generally does not present water solubility problems (Burt et al., 1995).

The Boron levels in the water for some of the Sites (table 2) may be toxic for some crops. The toxicity limit for sensitive crops ranges from 0.3 to 1 mg/L of Boron (Cuenca, 1989). Cotton can tolerate the Boron levels found in the water listed in table 2. However, the levels found may be toxic for pecans, another crop in the region.

Although chloride does not present a clogging potential, it may be toxic for some crops when the chloride exceeds 142 mg/L (Cuenca, 1989). The highest concentrations of chloride were found on sites C with 274mg/L and K with 517 mg/L (table 2).

Table 3. Fertilizer sources injected into the SDI systems that were evaluated in West Texas in 2008 and 2009.

Site	Nitrogen Fertilizer	Phosphorus Fertilizer
A	UAN 32-0-0	None
B	UAN 32-0-0	None
C	UAN 32-0-0	Miller Solugro 12-48-08
D	UAN 32-0-0	Phosphoric acid
E	UAN 32-0-0	Phosphoric acid
F	UAN 32-0-0	Phosphoric acid
G	UAN 32-0-0	None
H	UAN 32-0-0	None
I	UAN 32-0-0	None
J	UAN 32-0-0	None
K	UAN 32-0-0	Phosphoric acid
L	UAN 32-0-0	None
M	UAN 32-0-0	None
N	UAN 32-0-0	Phosphoric acid
O	UAN 32-0-0	Miller Solugro 12-48-08, humic acid and calcium lingo sulfate
P	UAN 32-0-0	None
Q	UAN 32-0-0	None
R	UAN 32-0-0	None

Iron and manganese can also represent a clogging potential when the iron concentrations of the water are greater than 0.1 mg/L and when sulfides greater than 2.0 mg/L are present. The water of the study sites had very small concentrations of iron and manganese (table 2); therefore clogging problems caused by these elements did not represent a threat.

The effect of specific water quality parameters and fertigation practices and their interactions on SDI system performance will be discussed in a later section.

Maintenance Programs

The most common maintenance practices were backflushing of the filters, periodic flushing of the driplines and PVC pipelines, and periodic injections of chlorine and acid (table 4).

Most of the producers backflushed the sand media filtration systems daily (table 4), except for four producers that backflushed every two days (Sites A, B, O, and R), two producers that backflushed every three days (Site I and J), and one producer who only backflushed every 4 days (Site H). The producer that had the disk filter backflushed every 12 h (Site M). Although all of the systems had automatic backflushing at a preset pressure differential, those systems with long intervals between backflushing may have been at risk. Backflushing intervals between 1 and 12 h were reported to be generally acceptable for media filtration by Nakayama et al. (2007) and Burt and Styles (2007) emphasized that media tanks should definitely be backflushed at least daily. A condition that has been termed as “rat holing” can occur when sand media filter tanks are not backflushed frequently enough. In “rat holing” large interconnected macropores essentially form tunnels within the media that allow inadequately filtered water to pass through and this also prevents sufficient pressure differential that would trigger an automatic backflush (Nakayama et al., 2007). The filtration system backflushing time varied from 0.5 min (Site M, grooved-disk filtration) to 4.0 min (Site J) with the majority of the sand media filtration systems being backflushed between 1.5 and 2.0 min (table 4). The required duration of backflushing is governed by the system flowrate and the amount of contaminant load and should be determined by the producer by visually examining the clarity of the backflush water at the end of the backflush cycle (Burt and Styles, 2007).

The driplines were generally flushed annually (table 4), although three producers did it once every two years (Sites G, O, and P) and another producer only once every three years (Site F). Although there have been improvements in emitter anti-clogging properties and filtration systems, Puig-Bargués et al. (2010b) concluded that periodic flushing of SDI systems is necessary for long-term performance. They also suggested that increasing the duration of flushing might be one of the more cost-effective ways of reducing the amount of sediments within the driplines.

The chlorine source used by the producers in all cases was sodium hypochlorite with a 12% concentration and was applied at approximately 0.47 L/ha. There was a great variability in the chlorination practices (table 4). Some producers had never injected chlorine and three injected every other year. Two other producers injected the chlorine after 7 and 8 years of use. Only two producers indicated they annually chlorinated their systems. This great variability suggests that SDI systems clogging concerns had not been emphasized when the producers installed their systems.

Most of the producers periodically injected sulfuric acid to lower the water pH below 3.5, except for the producer for Site N who had never injected acid (table 4). It can be noted that a much greater percentage of systems had periodic injections of acid than of chlorine. This could be indicative that the producers felt that their clogging hazards would be best handled by acidifying the water. Another possibility might be that more profitable acid products were being aggressively marketed in the region. The sulfuric acid that most producers used was a 95% concentration and they applied it at approximately 0.94 L/ha. One producer injected with N-pHuric 15/49 (Urea-Sulfuric-Acid) instead of sulfuric acid. This formulation is much less caustic than the highly concentrated sulfuric acid and should be considered preferable for safety reasons.

The possible effects of maintenance practices on possible SDI system performance degradation will be discussed in the next section.

Performance Evaluation of the SDI Systems

The 10 SDI systems evaluated in 2008 had been in place between 8 and 20 years and the eight systems evaluated in 2009 had been in place between 6 and 12 years (table 1). Although there were older SDI systems in the region that could have been selected, these other systems were only being used occasionally to irrigate pecan trees. There was very little correlation between SDI system longevity and performance of the system, as the oldest system (Site J at 20 years) had a DU_{lq} of 92 and a q_{var} of 0% (fig. 1 and table 5). The system with the smallest DU_{lq} was Site N with a longevity of 9 years and the system with the greatest q_{var} was Site I with a longevity of 15 years. These results agree with other published studies that reported system longevity is a poor indicator of microirrigation system performance (Hanson et al., 1995; Pitts et al., 1996).

System dripline length did not appear to have a consistent effect on system performance but it can be noted that the two longest systems (Systems L and O at 618 and 619 m, respectively) had relatively poor performance and the shortest system (System J at 183 m) had nearly the best performance (table 5).

There were three systems (System A, D, and E) where there were differences in how the performance was rated by the two performance parameters (table 5). System A had a q_{var} of 15%, yet had a DU_{lq} of 92 which can be explained by the fact that although friction losses and the resultant

Table 4. Typical maintenance practices as described by the producers for the SDI systems evaluated in West Texas in 2008 and 2009.

Site	Filter Backflushing Regimen Interval (h)	Filter Backflushing Regimen Duration (min)	Dripline Flushing	Chlorine Injection	Sulfuric Acid Injection (interval and amount)
A	48	2.50	Annual	First event after 8 years	Annually, lowering pH down to 3.5
B	48	2.50	Annual	First event after 7 years	Annually, lowering pH down to 3.5
C	24	2.00	Annual	Every other year	Annually, lowering pH down to 2.0
D	24	1.50	Annual	None	Annually, lowering pH down to 2.0 with N-pHuric 15/49
E	24	1.33	Annual	None	Annually, lowering pH down to 3.0
F	24	1.66	Every 3 years	Every third year	Every third year, lowering pH down to 3.1
G	24	1.00	Every other year	None	Every other year, lowering pH down to 3.0
H	96	2.00	Twice per year	After every 50 cm of irrigation to concentration of 10 mg/L	After every 50 cm of irrigation, lowering pH down to 3.0
I	72	4.00	Annual	After every 40 cm of irrigation to concentration of 10 mg/L	After every 40 cm of irrigation, lowering pH down to 3.5
J	72	4.00	Annual	After every 40 cm of irrigation to concentration of 10 mg/L	After every 40 cm of irrigation, lowering pH down to 3.5
K	24	1.50	Annually	Annually to concentration of 10 mg/L	Annually, lowering pH to 3.7
L	24	1.50	Annually	Every 2 years to concentration of 20 mg/L	Every 2 years, lowering pH to 3.5
M	12	0.50[a]	Annually	None for at least two years	None for at least two years
N	24	1.50	Annually	None	None
O	48	0.67	Every other year	Annually	Annually, lowering pH to 2.0
P	24	1.50	Every other year	Every 2 years to concentration of 20 mg/L	Every 2 years, lowering pH to 3.5
Q	24	1.50	Twice annually	Twice during life to concentration of 20 mg/L	Twice during life, lowering pH down to 3.5
R	48	0.67	Annually	Once during life to concentration of 20 mg/L	Once during life, lowering pH to 3.5

[a] Site M had a grooved-disk filtration system that generally require a relatively short backflushing duration.

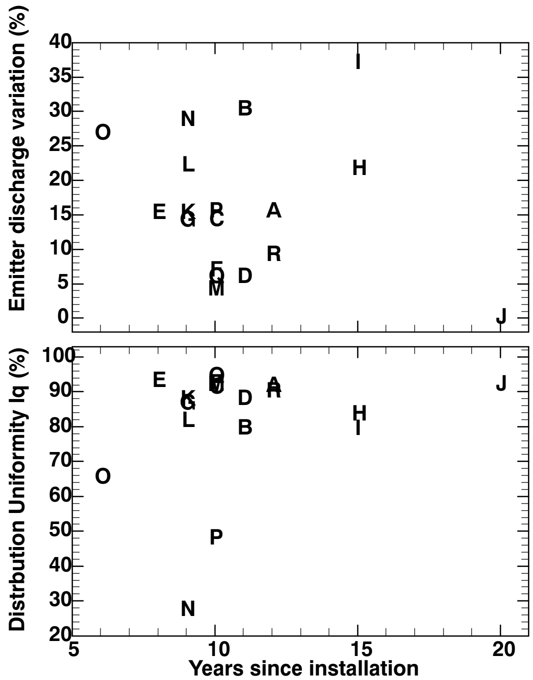

Figure 1. Emitter discharge variation and lower quartile distribution uniformity as affected by years since installation for 18 SDI systems evaluated in West Texas in 2008 and 2009. The letter symbols correspond to the 18 sites listed in table 1.

emitter discharge reductions were well correlated, there was little or no additional performance reductions due to emitter clogging which would have further reduced DU_{lq}. Similarly, System E had a good DU_{lq} of 93 but q_{var} was 15%, with the reason in this case being that System E was being operated at an excessive pressure (101 kPa) which resulted in considerable increase of flow rate and as a result, increased friction losses along the length of the dripline. System D which had a q_{var} of 6% had a slightly reduced DU_{lq} at 88 because of the random nature of reduced emitter discharge (i.e., emitter clogging) in that system. As stated earlier, the q_{var} calculations in this study were based on the average maximum and minimum emitter discharges obtained at the inlet and outlet of the driplines, so as to better account for hydraulic differences. The random nature of reduced emitter discharge in system D only slightly decreased these average maximum and minimum discharges. The reduced DU_{lq} did reflect the random nature of the reduced emitter discharge and included one particular emitter that had discharge approximately 60% of the average value. The differences in the performance parameters for these three systems emphasizes the utility of the two styles of performance parameters, in this case q_{var} to examine problems related to pressure variation and DU_{lq} to examine the aspects of random emitter clogging.

Six of the 18 SDI system had q_{var} less than 10% (Systems D, F, J, M, Q, and R) which is considered to be desirable performance (Clark et al., 2007). Additionally, all of these systems also had DU_{lq} greater than 90 with the exception of System D which was previously discussed.

Twelve of the 18 systems had q_{var} ranging between 14% and 37% and DU_{lq} ranging from 48 to 92 (table 5). Of these 12 systems, the excessive q_{var} could be explained by q_{pvar} for 7 of the systems (Systems A, B, C, H, K, L, and P). Based on analysis of the measured pressure data at various distances along the dripline and from limited operational information provided by the producers (e.g., assumed system flowrate and number of zones) it is suspected that insufficient zone flowrate caused the poor performance of four of these seven systems (Systems A, H, L, and P). System P had the second lowest DU_{lq} of the 18 evaluated systems and also had some fully clogged emitters. It is possible that System P's low operating pressure combined with below average maintenance (table 4) further contributed to its poor performance. It seems likely the performance of these four systems could be improved by improving the system flowrate

Table 5. Performance characteristics of the 18 SDI systems evaluated in West Texas in 2008 and 2009.

Site	Inlet Pressure (kPa)	Mid-point Pressure (kPa)	Outlet Pressure (kPa)	P_{var} (%)	Inlet Emitter Discharge (L/h)	Mid-point Emitter Discharge (L/h)	Outlet Emitter Discharge (L/h)	q_{var} (%)	qp_{var} (%)	Excessive q_{var} > 10%	q_{var} >10%, but Explained by qp_{var}	DU_{lq}
A	56	40	36	36	1.26	1.12	1.07	15	18	Yes	Yes	92
B	87	53	41	52	1.06	0.92	0.74	30	28	Yes	Yes	79
C	128	99	91	29	1.23	1.06	1.13	14	14	Yes	Yes	91
D	53	46	44	18	0.83	0.78	0.82	6	9	–	–	88
E	101	89	88	13	0.90	0.78	0.76	15	6	Yes	No	93
F	32	24	21	34	0.97	0.95	0.90	7	17	–	–	92
G	37	31	30	18	0.54	0.50	0.47	14	9	Yes	No	87
H	24	16	15	37	0.86	0.79	0.68	22	19	Yes	Yes	83
I	48	34	31	35	1.02	0.80	0.64	37	18	Yes	No	79
J	44	35	35	20	0.38	0.39	0.38	0	11	–	–	92
K	80	58	45	44	0.99	0.90	0.84	15	23	Yes	Yes	88
L	98	70	60	39	1.04	0.81	0.86	22	20	Yes	Yes	82
M	76	67	63	17	0.98	0.94	0.94	4	8	–	–	92
N	110	95	93	16	1.05	0.78	0.75	29	7	Yes	No	27
O	133	114	109	19	0.86	0.85	0.63	27	9	Yes	No	65
P	26	20	21	26	0.62	0.61	0.52	15	10	Yes	Yes	48
Q	60	41	39	35	0.92	0.87	0.87	6	17	–	–	94
R	68	59	59	14	1.05	0.96	0.95	9	7	–	–	90

when that is possible (e.g., pump adjustment or repair), reducing the number of zones being irrigated simultaneously, or perhaps by splitting oversized zones into multiple smaller zones. The zone inlet pressures for Systems H and P were particularly low at 24 and 26 kPa, respectively, which is approximately 30% to 32% of the typical operating pressure for this model of dripline. The emitter discharge for System C also was explained by pressure variation, but the operational problem for this system appeared to be excess pressure at the inlet (128 kPa) which resulted in excessive emitter discharge at the inlet, and too much friction loss along the 488-m dripline. Systems B and K experienced very large pressure drop between the inlet and the system midpoint that could not be primarily explained by excessive inlet pressure. Possible reasons for such a large pressure drop might be a partially compressed dripline that would have reduced flowrate (Hills et al., 1989) that could have been caused by overburden from non-bridging soils or by soil compaction (Lamm and Camp, 2007). However, neither of these conditions is known to have existed in this field. System K was a reasonably long system at 549 m in length, but if excessive length was the primary reason for reduced performance it should have been reflected by friction losses. System K had very high levels of total dissolved solids, calcium, and magnesium which might lead to precipitates within the dripline under some conditions. The driplines might be partially obstructed by large amounts of sediments or chemical precipitates, although this seems somewhat unlikely as there were no severely or totally clogged emitters in the System B and K evaluations. An abrupt positive increase in field slope (uphill) could also be responsible for this pressure drop but the land slope on these systems was relatively low (less than 0.1 %) and there was no noted observations of excessive undulations recorded in the field notes. It seems likely that a number of reasons, each individually smaller in scope, combined to reduce the performance of Systems B and K.

There were five systems (Systems E, G, I, N, and O) with q_{var} exceeding 10% that were not explained by q_{pvar} (i.e., positive differences in q_{var} - q_{pvar} were greater than an arbitrary 5%). Three of these systems (Systems E, N, and O) had excessive operating pressures ranging from 101 to 133 kPa. System E had never been chlorinated, so it is possible the producer had been trying to compensate for decreased emitter discharge by increasing the pressure. System N, the poorest performing system of the 18 evaluated systems, with q_{var} of 29 and DU_{lq} of 27 also never had been chlorinated or acidified. System N contained some severely and fully clogged emitters, so the excessive operating pressure on this system may have been attempted to improve performance. System O also had a maintenance issue that should be addressed in that its sand media filtration system was only backflushed every two days instead of daily backflushing and the duration of backflushing was only 40 s. System O had the fourth highest q_{var} at 27% and the third lowest DU_{lq} at 65, and it possessed several severely clogged emitters. Periodic maintenance would be a much less expensive alternative to constant elevated operating pressure. Similarly, the 3-day backflushing interval of System I may be indicative of poor maintenance that was responsible for it having the highest q_{var} (37%) of all 18 evaluated systems and the fourth lowest DU_{lq} (79). However, two zones were being operated simultaneously for System I and the large decrease in dripline pressure near the end of the system may also be indicative of insufficient system flowrate. System G was operated at a relatively low pressure (inlet pressure of 37 kPa) and had never been chlorinated (table 4) and this may have contributed to its excessive q_{var} of 14% and its DU_{lq} of 87. It is possible that even after several years of neglected maintenance the performance of Systems E, G, I, N, and O might be improved as Lamm et al. (2002) indicated that aggressive maintenance and flushing after four years of irrigation with beef feedlot effluent that severely reduced dripline flowrates were restored to nearly 80% and 97% of their original values.

Overall, the results suggest that design and/or operational problems decreased the performance of 7 of the 12 systems. In general, the system performance was best when the ratio of dripline inlet pressure (i.e., the point where hydraulically pressure is usually at a maximum) to the nominal design pressure specified by the manufacturer was between 0.65 and 1.00 (fig. 2). Only 6 of the 18 systems were being operated in this manner with the average difference being ±36% from the nominal design pressure. Only one system had an inlet emitter discharge (table 5) within 6% of the nominal emitter discharge specified by the manufacturer (table 1) with the average discharge varying by ±30% (fig. 3). These operational problems indicate the importance of the producers having been provided and retaining good records of what was installed for their system and having been instructed with and then following good operational procedures.

Analysis of the performance results and maintenance records suggests that many of the systems also had degradations in system performance due to poor maintenance

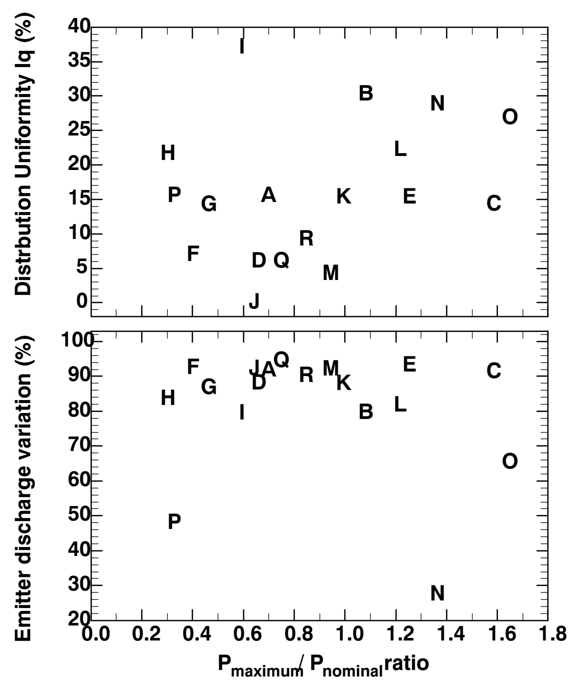

Figure 2. Emitter discharge variation and lower quartile distribution uniformity as affected by the ratio of the dripline inlet (maximum) pressure to the nominal design pressure specified by the manufacturer for 18 SDI systems evaluated in West Texas in 2008 and 2009. The letter symbols correspond to the 18 sites listed in table 1

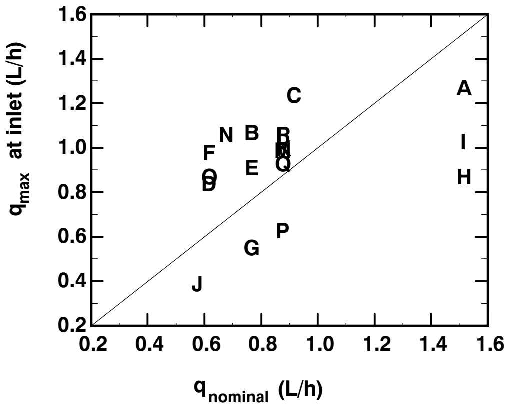

Figure 3. Maximum emitter discharge at the dripline inlet as related to the nominal emitter discharge specified by the manufacturer for 18 SDI systems evaluated in West Texas in 2008 and 2009. The letter symbols correspond to the 18 sites listed in table 1.

that would be further exacerbated by source water quality issues. The lack of annual chlorination in at least 13 of the 18 systems should be a cause for concern. Additionally, the lack of daily backflushing of sand media filtration systems in seven of the 18 SDI systems may have affected performance and could impact SDI system longevity.

Conclusions

The system performance of a total of 18 different SDI systems that had been operated between 6 and 20 years were evaluated in the years 2008 and 2009. In general, the uniformity of these older SDI systems was good to excellent with the emitter discharge variation (q_{var}) less than 10% for six systems and the lower quartile distribution uniformity (DU_{lq}) being also greater than 90% for six systems. Five of the 18 SDI systems had q_{var} greater than 20% and DU_{lq} less than 80%. System performance and system longevity were poorly correlated with the oldest system (20-years old) having the best uniformity.

There were appreciable differences in how the two uniformity performance parameters (q_{var} and DU_{lq}) rated 3 of the 18 SDI systems which emphasizes the utility of using more than one performance parameter for evaluations. In the case of this study, q_{var} was used to improve determination of performance degradation due to design and/or operational hydraulic concerns, while DU_{lq} could provide additional information about random emitter clogging within the system.

Those systems with the best uniformity were being operated with pressures between 65% and 100% of the nominal design pressure, but two-thirds of the SDI systems were operated outside of this range. One-third of the systems did not receive daily backflushing of their filtration systems although this would be a recommended maintenance practice. Water hardness would be a water quality concern for emitter clogging according to traditional classification criteria for microirrigation systems for all 18 SDI systems. Annual chlorination was not performed on over 70% of the systems. A much larger proportion of producers used periodic acidification than those using chlorination which raises the question about whether acidification was being perceived as the correct solution for the emitter clogging hazard or whether the more expensive acidification was being aggressively marketed in the region. Poor operating procedures, poor maintenance, or the combination of the two potentially explained nearly all of the observed uniformity problems. None of the producers had been given or still retained installation records that would have been valuable in accessing the appropriateness of current system operation and would also serve as a corrective guide for future operation.

Overall, perhaps, the results should not be viewed as an accurate representation of uniformity of older SDI systems currently being used in West Texas. It would seem to the authors a better use of the results would be to highlight the variability in SDI system performance that can occur due to management, maintenance and source water quality.

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