ASSESSMENT OF MICROIRRIGATION FIELD DISTRIBUTION UNIFORMITY PROCEDURES FOR PRESSURE-COMPENSATING EMITTERS UNDER POTENTIAL CLOGGING CONDITIONS

Research Brief

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HIGHLIGHTS

- Distribution uniformity of the lower quartile (DU_{lq}) was assessed in three microirrigation subunits with three procedures that used different locations and different numbers of sampled emitters.
- Using reclaimed effluent as the water source, performance was periodically measured for a total duration of 1000 h.
- Emitter clogging and the locations of sampled emitters greatly affected DU_{lq}.
- None of the procedures accurately assessed DU_{lq} if more than 4% of the emitters were fully clogged.

ABSTRACT. *Proper water distribution uniformity is important for successful use of microirrigation systems. Consequently, consistent system monitoring and periodic distribution uniformity assessments can help determine the performance of a microirrigation system and identify possible problems that should be corrected. When using irrigation water with a greater clogging risk, such as reclaimed effluent, emitter clogging can seriously affect distribution uniformity. In this study, distribution uniformity was measured at three times (0 h, 500 h, and 1000 h of operation) in a microirrigation system that used reclaimed effluent. Emitter discharge values were obtained for each emitter in the system (three subunits consisting of four driplines each with 226 pressure-compensating emitters on each dripline), and the distribution uniformity of the low quartile (DU_{lq}) was calculated for each subunit. These comprehensive DU_{lq} values were compared with those calculated by three estimation procedures developed by Merriam and Keller, Burt, and Juana et al., which use different sampling locations and different numbers of sampling points. Results showed strong influence of emitter clogging and the location of the sampled emitters on DU_{lq} values. Using this data set, the Merriam and Keller procedure had the greatest root mean square error (RMSE = 41.8%), the Burt procedure resulted in an intermediate value (RMSE = 5.9%), and the Juana et al. procedure had the lowest (RMSE = 3.2%) when most of the completely clogged emitters (about 1% of the total) were located at the ends of the driplines. Further speculative analysis in which complete clogging was allowed to migrate to the farthest distal emitters for the Burt and Juana et al. procedures indicated that none of the procedures accurately assessed the actual complete DU_{lq}. These results suggest that none of these procedures alone are successful at assessing system-wide distribution uniformity when substantial clogging exists.*

Keywords. *Drip irrigation, Effluent, Emitter clogging, Flow variation, Wastewater.*

Microirrigation is an irrigation technique that can achieve greater water application uniformity and efficiency. Uniformity at the subunit level is primarily affected by the following factors, which are listed in order of importance: clogging, number of emitters per plant, emitter coefficient of variation, emitter exponent, emitter discharge response to water temperature, and pressure differences (Solomon, 1985). All microirrigation systems should be periodically evaluated to ensure that the performance of the system is maintained at or near the originally designed uniformity (Wu et al., 2007). Theoretically, discharge from all the emitters in the field should be collected, which is often impractical due to the large number of emitters. Thus, several sampling procedures have been developed for assessing microirrigation water distribution uniformity, and they often differ in the number of sampled emitters and the emitter locations within the system.

The water distribution uniformity of microirrigation systems can be expressed using different uniformity parameters, such as the Christiansen uniformity coefficient (Christiansen, 1942), coefficient of variation (CV), statistical

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uniformity coefficient (Bralts et al., 1981), and distribution uniformity (Merriam and Keller, 1978). A field measurement often used to characterize uniformity in microirrigation systems is the lower quartile distribution uniformity (DU_{lq}), defined as:

$$DU_{lq} = 100\left(\frac{q_{25}}{\bar{q}}\right) \quad (1)$$

where q_{25} is the average discharge of the 25% of the emitters with the lowest discharge (L h^{-1}), which is usually assumed as an estimation of the minimum emitter discharge, and $\bar{q}$ is the average discharge of all the emitters tested (L h^{-1}).

The DU_{lq} depends mainly on the hydraulic design, manufacturing CV, and emitter clogging (Barragán et al., 2006). Perea et al. (2013) found that DU_{lq} decreased with a greater number of emitters, reduced operating pressure, and a higher manufacturing CV.

Various procedures have been proposed to sample emitters for the calculation of DU_{lq} for microirrigation systems, such as those described by Merriam and Keller (1978), Burt (2004), and Juana et al. (2007). The Merriam and Keller (1978) procedure selects four driplines within an irrigation submain. One of the selected driplines should be located near the beginning and another near the end of the submain, with the other two driplines equally spaced between the first and last driplines (i.e., at 1/3 and 2/3 of the total submain length). Four pairs of emitters are selected along each of the four driplines, located at the inlet, at 1/3 and 2/3 of the dripline length, and at its distal end. At each of the 16 resulting sampling points, dripline pressure is measured, and the average discharge of two contiguous emitters is obtained.

Juana et al. (2007) criticized these selected locations because they represent neither the mathematical probability of the mean discharge of all the emitters in a subunit nor their variance. However, the use of distal locations suggested by Merriam and Keller (1978) still provides useful information on the head losses in driplines and submains and should not be disregarded. To overcome these issues, Juana et al. (2007) suggested selecting four different dripline sampling positions to ensure a more accurate estimation of the mean and variance of the emitter discharge for the whole irrigation subunit. A shape factor, which depends on the length of the first and last driplines of the irrigation subunit, is used for selecting the specific sampling locations in rectangular and trapezoidal irrigation units.

Burt (2004) presented a procedure developed by the Irrigation Training and Research Center (ITRC) of California Polytechnic State University for evaluating drip and microsprayer irrigation systems. Different distribution uniformity components related to pressure differences, unequal spacing and drainage, clogging, wear, and manufacturing variation are also considered in this procedure, which requires more pressure and emitter discharge measurements. Three locations within the system are used for assessing emitter discharge differences, and there must be no appreciable pressure difference between the individual emitters at each location. The first location is near the water source, where the cleanest emitters are anticipated to be found. The second location is near mid-length of a dripline near the middle of the field. At both of these locations, emitter discharges from 16 emitters are measured. The third location is at the end of the most distant dripline, which is usually the most contaminated region of the system. At this last location, discharge is measured from 28 contiguous emitters. Thus, emitter discharge is obtained from 60 emitters total.

The goal of this study was to compare the results of distribution uniformity assessments using the different DU_{lq} procedures under field conditions for a microirrigation system with pressure-compensating emitters that used reclaimed effluent and consequently was more prone to clogging.

Materials and Methods

Experimental Setup

The experiment was carried out using three microirrigation subunits, each with a different type of sand filter and with four driplines of the same characteristics (fig. 1). Because each of the subunits had a different filtration system, no statistical comparison between subunits is warranted, nor are any differences discussed in that context. Each of the four driplines was 90 m long and had 226 emitters spaced 0.4 m apart. Pressure-compensating (PC) in-line emitters (Uniram AS 16010, Netafim, Tel Aviv, Israel), with a nominal discharge of 2.3 L h^{-1}, nominal working pressure range of 50 to 400 kPa, and manufacturing CV of 0.03 as specified by the manufacturer, were used. The emitter discharge exponent was experimentally determined in this study as 0.02. The average slope of the field was 0.85%.

The filtration systems used in the three subunits were a sand filter with dome underdrains (FA-F2-188, Regaber, Parets del Vallès, Spain), a sand filter with an arm collector underdrain (FA1M, Lama Sistemas de Filtrado, Gelves, Spain), and an experimental prototype sand filter with a porous media underdrain (Bové et al., 2017). All the filters were filled with silica sand (CA-07MS, Sibelco Minerales, Bilbao, Spain) with an effective diameter (D_e, opening size that will pass 10% of the sand) of 0.48 mm and a coefficient of uniformity (ratio of the opening sizes that will pass 60% and 10% of the sand) of 1.73. The filters were automatically backwashed when the total pressure drop across them, as measured by pressure transducers, reached 50 kPa. The backwashing time was 3 min throughout the experiment. During this time, backwash water did not reach driplines. The water used for backwashing came from a tank that stored filtered water.

The irrigation water was reclaimed effluent from the Celrà (Girona, Spain) wastewater treatment plant, which treats urban and industrial effluents using a sludge process. Chlorine was continuously injected using a membrane pump (DosTec AC1/2, ITC, Sta. Perpètua de la Mogoda, Spain) and reached a concentration of 2 mg L^{-1} in the water after being filtered. When the sand filters were backwashed, the backwash water entering the filters was chlorinated to reach a concentration of 4 mg L^{-1}. The reclaimed effluent was pumped with a multicellular centrifugal pump (CR-15-4, Grundfos, Bjerringbro, Denmark). Because the filtrated flow rate was greater than that needed for the driplines, a

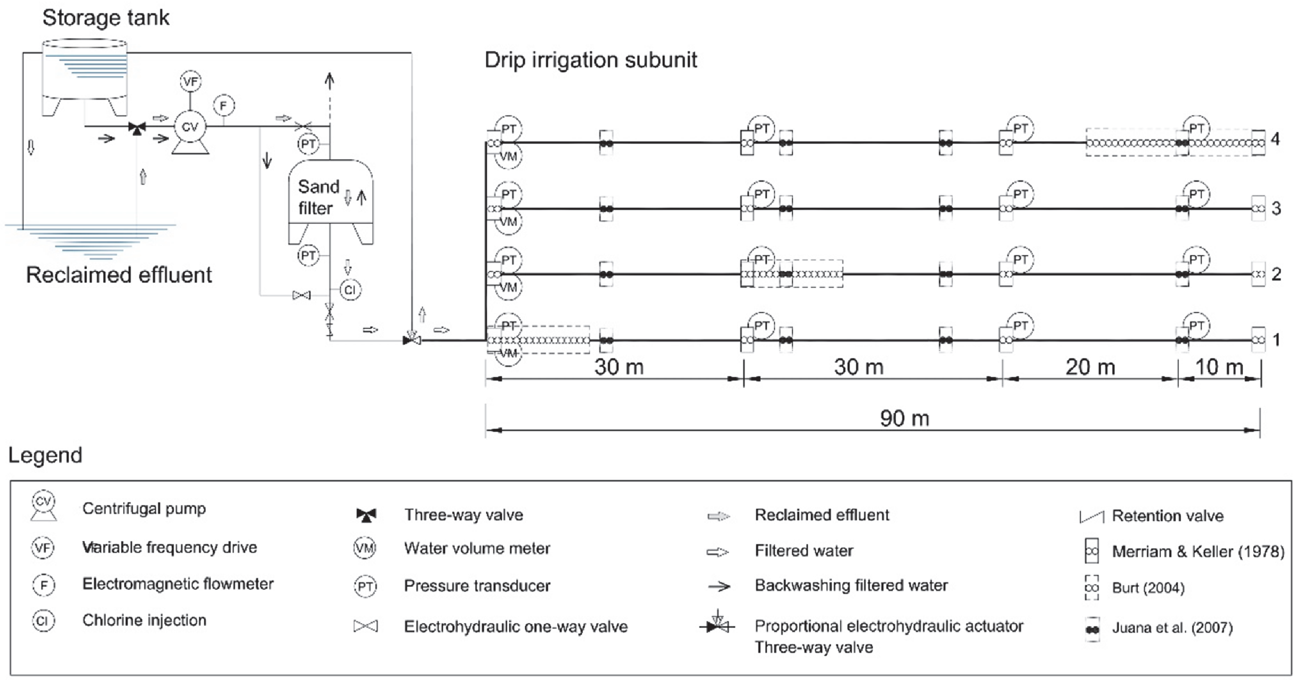

Figure 1. Experimental setup and locations of emitters used for computing DU_{lq} with the different procedures.

proportional electrohydraulic actuator (SKD32, Siemens, Munich, Germany) operated a three-way valve (VXG41, Siemens, Munich, Germany) so that the excess flow was delivered to the 3000 L storage tank (Aquablock, Shütz, Selters, Germany) that was used for filter backwashing.

Because the three subunits did not operate simultaneously, the main effluent parameters were determined to assess if there were substantial differences in irrigation water characteristics during the experiments. Effluent electrical conductivity, pH, and temperature at the filter inlets, and turbidity and dissolved oxygen at the filter outlets, were measured using sensors (CLS21-C1E4A, CPS11D-7BA21, CUS31-A2E, and COS61-A1F0, respectively, Endress+Hauser, Gerlingen, Germany). Collected data were recorded every minute in a supervisory control and data acquisition system (SCADA) previously developed (Duran-Ros et al., 2008) and adapted to this experiment using transmitters (LIQUISYS-M CLM253-CD0010, CPM253-MR0010, CUM253-TU0005, and COM253-WX0015, Endress+Hauser, Gerlingen, Germany). Table 1 presents the mean values of pH, temperature, conductivity, dissolved oxygen, and turbidity recorded during the experiment.

Despite the fact that the numerical differences for most of the parameters at the subunit inlets were small, significant differences ($p < 0.05$) were observed between some subunits. According to the Bucks et al. (1979) classification, there was a moderate chemical clogging hazard regarding pH for all three subunits. Greater temperatures increase biofilm growth in emitters (Yan et al., 2009). Therefore, significantly greater ($p < 0.05$) water inlet temperature at subunit 1 compared to subunit 3 may have promoted the formation and growth of biofilms, which are closely related to emitter clogging (Zhou et al., 2013). Although significant differences ($p < 0.05$) were observed in turbidity at the filter outlets, the risk of physical clogging (i.e., clogging from inorganic particles) was low for all three subunits. All these variations are consistent with the typical variability associated with reclaimed effluent.

Water meters (405S DN15, Sensus, Raleigh, N.C.) were placed at the beginning of each dripline, and the dripline inlet volume was recorded each minute in the SCADA system using pulse units (HRI-A1, Sensus, Raleigh, N.C.). The average cumulative volumes for each dripline at the end of experiment are shown in table 1. Periodically, effluent samples were taken, and the total suspended solids (TSS) were analyzed in the laboratory by gravimetry (APHA, 2017). The TSS and turbidity were statistically correlated, and the following equation was obtained with a regression coefficient (R^2) of 0.93, $p < 0.01$, and standard error of estimate of 1.72 mg L^{-1}:

$$TSS = 1.53(\text{turbidity}) + 0.03 \quad (2)$$

Table 1. Means and standard deviations of effluent parameters at the filter inlets and outlets, cumulative dripline volumes, and estimated total suspended solids (TSS) passing through each dripline during the experiment. Different letters following values in the same column indicate significant differences (p < 0.05) between irrigation subunits.

Irrigation Subunit	Filter Inlet pH	Filter Inlet Temperature (ºC)	Filter Inlet Electrical Conductivity (dS m^{-1})	Filter Outlet Dissolved Oxygen (mg L^{-1})	Filter Outlet Turbidity (FNU)	Cumulative Dripline Volume (m^3)	Estimated Dripline TSS Load (kg)
1	7.33 ±0.20 b	20.6 ±3.3 a	2.64 ±0.46 a	3.3 ±0.8 b	4.5 ±1.2 b	529 ±2 c	3.6 b
2	7.43 ±0.24 a	20.1 ±3.5 ab	2.46 ±0.53 b	3.6 ±1.0 a	4.2 ±1.4 c	541 ±4 b	3.5 c
3	7.31 ±0.22 b	19.78 ±3.6 b	2.63 ±0.44 a	3.3 ±0.7-b	4.9 ±1.1 a	551 ±5 a	4.1 a

where TSS is the total suspended solids (mg L^{-1}), and turbidity is expressed in formazin nephelometric units (FNU). Using the cumulative volumes and equation 2 for converting turbidity into TSS, the total mass of solids applied through each subunit dripline was estimated (table 1). The results indicate that there were small but statistically significant differences ($p < 0.05$) in dripline volume and estimated TSS load for each subunit. These differences were due to small variations in actual operating times (which were 1003, 1033, and 1017 h for subunits 1, 2, and 3, respectively) and to emitter clogging, which reduced the subunit flow rate with time. Differences in the estimated suspended solids entering the driplines had the same trend as filter outlet turbidity because turbidity was used for estimating the total solids load.

SYSTEM OPERATION

The experiment lasted 1000 h, from March to November 2018. Operation was interrupted in June due to a breakdown of the turbidity sensors. Whenever possible, six daily irrigation sessions of 4 h each (i.e., two daily sessions of 4 h for each subunit) were conducted. In practice, the irrigation sessions were as homogeneous as possible, which was not always possible due to small breakdowns that prevented the use of an irrigation subunit for a certain period. When these breakdowns were resolved, the operating time of the affected subunits was increased to equalize the hours of operation. No dripline flushing was performed during the course of the experiment.

EXPERIMENTAL ASSESSMENT OF EMITTER PERFORMANCE

Discharge for all the emitters on all the driplines in the three subunits (a total of 2712 emitters) was measured in the experimental field at the beginning (0 h), middle (500 h), and end of the experiment (1000 h). The discharge of 20 emitters was collected simultaneously for 5 min in collection dishes and measured in an appropriate-size graduated cylinder, and the procedure was then repeated for the next set of 20 emitters. The measurement of emitter discharge required about 20 h to complete at each measurement time (0 h, 500 h, and 1000 h) because of the large number of emitters. In addition, the number and location of each completely clogged emitter was recorded at each time. The emitter discharge values allowed computation of the distribution uniformity (DU_{lq}) using equation 1 and the three estimation procedures.

During the emitter discharge measurements, pressure was also determined at four locations on each dripline (at the beginning, 1/3 of the dripline length, 2/3 of the dripline length, and at the end) using a digital manometer (Leo 2, Keller, Winterhur, Switzerland), with a precision of ±0.07%, through fittings added to the driplines at each location. Pressure uniformity (U_{plq}) (Bliesner, 1976) was calculated according to the following equation:

$$U_{plq} = 100\left(\frac{p_{25}}{\overline{p}}\right)^{x} \tag{3}$$

where p_{25} is the average pressure of 25% of the locations with the lowest pressure (kPa), $\overline{p}$ is the average pressure of all the locations (kPa), and x is the emitter discharge exponent.

The DU_{lq} was computed using the locations of the emitters required by the Merriam and Keller (1978), Burt (2004), and Juana et al. (2007) procedures. According to Merriam and Keller (1978), the discharge of two contiguous emitters located at the beginning, at 1/3 of the dripline length, at 2/3 of the dripline length, and at the end of each of the four driplines was averaged. For the Burt (2004) procedure, the discharge of emitters 78 to 93 for the first and second driplines and of emitters 199 to 226 for the fourth dripline were used. For the Juana et al. (2007) procedure for a rectangular subunit, which has a shape factor of 0 because the dripline lengths are all the same, locations at 10%, 40%, 59%, and 90% of the length (i.e., emitters 22-23, 90-91, 135-136, and 202-203) of each dripline were selected. The locations of the different emitters required for each procedure are shown in figure 1.

DATA ANALYSIS

The frequency of the emitter discharge values was computed for each subunit. Normality of the emitter discharge values was assessed with the Kolmogorov-Smirnov and Shapiro-Wilk tests using SPSS (IBM, Armonk, N.Y.). Mean separations and regressions between uniformity indices were obtained with the same software. The root mean square error (RMSE) was computed using the following equation:

$$\text{RMSE} = \sqrt{\frac{\left(DU_{lq\ real} - DU_{lq\ method}\right)^2}{N}} \tag{4}$$

where $DU_{lq\ real}$ is the DU_{lq} computed with all the emitter discharges, and $DU_{lq\ method}$ is the DU_{lq} computed with any one of the estimation procedures, i.e., Merriam and Keller (1978), Burt (2004), and Juana et al. (2007), that were evaluated in this study, and N is the number of observations.

RESULTS AND DISCUSSION

Experimental values for the emitter discharges and dripline pressures at the three measurement times are shown in tables 2 and 3, respectively. The average emitter discharge for all three subunits was reduced by 7.6% in the first 500 h of operation and by an additional 3.1% by the end of the experiment at 1000 h (2.50, 2.30, and 2.22 L h^{-1}, respectively). The average CV of the emitter discharges increased from 0.04 at the beginning of the experiment (relatively close to the manufacturing CV of 0.03) to 0.12 at the end of the experiment, which was a 211% increase. In a field assessment in California sampling 324 emitters with 2 L h^{-1} discharge that had been in place for five years, Styles et al. (2008) found a CV of 0.13, which was slightly greater than that observed at the end of the present experiment. Styles et al. (2008) used water from an aqueduct, so the CV of emitter discharges using reclaimed effluent might be similar to those obtained after some years of using surface water. Using fresh water from an aquifer with appropriate maintenance practices, Lamm and Rogers (2017) found a CV of approximately 0.03 in field measurements of subsurface drip emitters after 26.5 years of operation.

Table 2. Emitter discharge values, indexes, and normality test results for the three subunits (1, 2, and 3) at three measurement times.

Statistic[a]	0 h				500 h				1000 h			
	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean
N	904	904	904	2712*	904	904	904	2712*	904	904	904	2712*
$\bar{q}$ (L h^{-1})	2.51	2.48	2.50	2.50	2.29	2.28	2.31	2.30	2.21	2.20	2.26	2.22
SD (L h^{-1})	0.09	0.11	0.07	0.09	0.20	0.15	0.09	0.15	0.27	0.28	0.22	0.26
CV	0.04	0.05	0.03	0.04	0.09	0.07	0.04	0.06	0.12	0.13	0.10	0.12
q_{25} (L h^{-1})	2.39	2.33	2.41	2.38	2.14	2.13	2.19	2.15	1.98	1.94	2.08	2.00
DU_{lq}	95.4	94.0	96.3	95.2	93.2	93.4	95.0	93.8	89.5	88.2	91.8	89.8
Skewness	-2.23	1.80	-2.45	-	-8.46	-7.89	-6.21	-	-6.21	-5.58	-7.51	-
Kurtosis	9.63	4.41	8.68	-	84.6	94.0	44.9	-	44.9	37.8	67.2	-
K-S	<0.001	<0.001	<0.001	-	<0.001	<0.001	<0.001	-	<0.001	<0.001	<0.001	-
S-W	<0.001	<0.001	<0.001	-	<0.001	<0.001	<0.001	-	<0.001	<0.001	<0.001	-

[a] N = number of emitters (* = total number of measured points), $\bar{q}$ = average emitter discharge, SD = standard deviation, CV = coefficient of variation, q_{25} = average discharge of the 25% of the emitters with the lowest discharge, DU_{lq} = distribution uniformity of lower quartile, and K-S and S-W = p-values for Kolmogorov-Smirnov and Shapiro-Wilk tests (not normal if $p < 0.05$).

Table 3. Pressure values and related indexes for the three subunits (1, 2, and 3) at three measurement times.

Statistic[a]	0 h				500 h				1000 h			
	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean
N	16	16	16	48*	16	16	16	48*	16	16	16	48*
$\bar{p}$ (kPa)	130	130	130	130	134	129	145	136	121	121	136	121
SD (kPa)	32	32	31	31	29	30	25	28	22	24	29	25
CV	0.24	0.24	0.24	0.24	0.21	0.23	0.17	0.21	0.18	0.18	0.22	0.19
p_{25} (kPa)	101	101	102	101	105	91	122	106	100	112	109	107
U_{plq}	99.5	99.5	99.5	99.5	99.5	99.3	99.7	99.5	99.6	99.6	99.6	99.6

[a] N = number of measuring points (* = total number of measured points), $\bar{p}$ = average pressure, SD = standard deviation, CV = coefficient of variation, p_{25} = average pressure of the 25% of the locations with the lowest pressure, and U_{plq} = pressure uniformity of lower quartile.

In addition to water quality, other factors can affect emitter discharge. Enciso-Medina et al. (2011) observed that uniformity problems in commercial subsurface drip irrigation systems were related to incorrect operating pressure, lack of chlorination, and inadequate filtration system backwashing. Greater CVs of emitter discharges in the present experiment were directly related to emitter clogging, which began to be observed at 500 h. Emitter clogging also had an obvious effect on the average discharge of the 25% of the emitters with the smallest discharge (q_{25}), which decreased from an average 2.38 L h^{-1} at 500 h (4.8% reduction) to 2.00 L h^{-1} at 1000 h (10.1% reduction).

Pressure values across the driplines were relatively constant throughout the experiment. However, an approximately 11% difference in average pressure was observed between 500 h and 1000 h due to small variations in the head pressure and due to clogging of the screens of the water meters installed at the beginning of each dripline. Pressure was reduced within the driplines due to head loss caused by the emitters and by the sensors used for control, but the average pressures of the lower quartile (p_{25}) were only 5.6% different between the three measurement times (0 h, 500 h, and 1000 h) and were always well above 50 kPa, which was the specified minimum working pressure of the PC emitters used in the experiment. Near the minimum working pressure required for pressure compensation, PC emitter discharge can become unstable, and this can cause a sharp decrease in DU_{lq} (Perea et al., 2013). Overall, U_{plq} was relatively constant during the experiment, with a minimum value of 99.3, meaning that the pressure distribution along the driplines was uniform and should not have appreciably affected the DU_{lq}, particularly for PC emitters. Thus, the DU_{lq} could be primarily explained by emitter clogging because the manufacturing CV was also very low (~0.03).

The frequency of discharge for all emitters in the three subunits at the three measurement times and their distribution plots are shown in figure 2. The emitter discharge did not follow a normal distribution, according to both the Kolmogorov-Smirnov and Shapiro-Wilk tests (table 2), at any of the measurement times (0 h, 500 h, or 1000 h) for each subunit. Normal distribution of emitter discharge is a common assumption in estimations of microirrigation uniformity (Bralts and Kesner, 1983), although normal distributions do not always occur in all emitter discharge experiments (Noori and Al Thamiry, 2012). With the increase in operating time, the range of the emitter discharges widened due to emitter clogging; consequently, their distribution showed more skewness and kurtosis (fig. 2).

Table 4 indicates the locations of the emitters that were completely clogged, which were at the distal ends of the driplines. Thus, after 1000 h, in most of the driplines, the last two emitters (emitters 225 and 226, at 99.6% to 100% of the dripline length) were fully clogged Several studies have shown that it is more probable to find completely clogged emitters at the distal ends of driplines, especially when low-quality water, such as reclaimed effluent, is used because of the low flow velocities that allow more sedimentation and consequently more clogging (Ravina et al., 1992; Trooien et al., 2000; Puig-Bargués et al., 2010). The number of completely clogged emitters at the end of the experiment was greater for subunit 1 (11 emitters in four driplines) than for subunit 2 (9 emitters) and subunit 3 (6 emitters) (table 4).

Estimated values of DU_{lq} (table 5) differed because all three estimation procedures only used a small fraction of the total emitters, while all the emitter discharges were considered as the control treatment in this study. The Merriam and Keller (1978) procedure had the smallest and significantly different ($p < 0.001$) DU_{lq} values at 1000 h, primarily because it included all the clogged emitters located at the ends

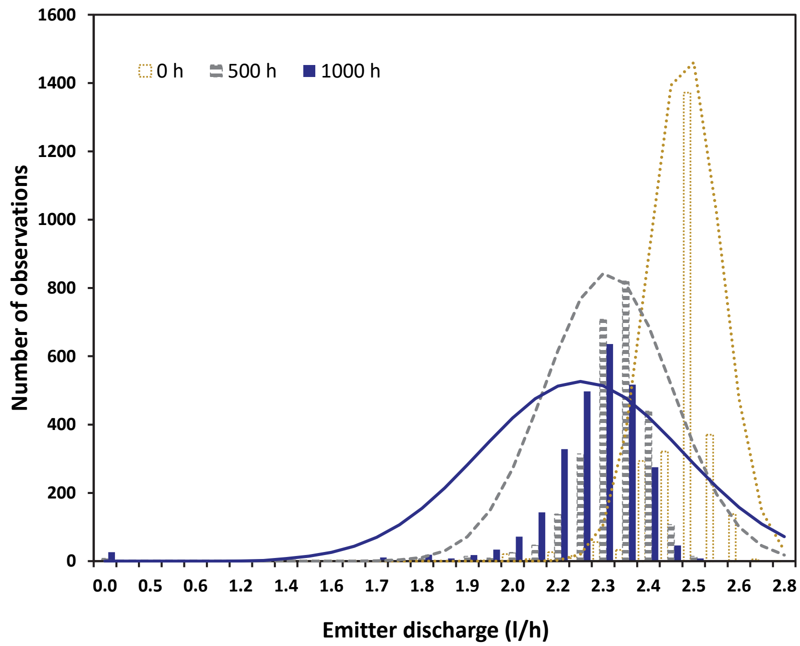

Figure 2. Frequency of discharge of all emitters in all subunits at different times (bars) and calculated distributions (lines).

Table 4. Emitter numbers (from 1 to 226) that were completely clogged in each dripline and their locations (% of total length).

Subunit	Dripline	Locations of Completely Clogged Emitters (and % of Dripline Length) 500 h	1000 h
1	1	226 (100%)	226 (100%)
	2	-	226 (100%)
	3	225, 226 (99.6% to 100%)	221, 223, 224, 225, 226 (97.3%, 97.8% to 100%)
	4	224, 225, 226 (99.1% to 100%)	223, 224, 225, 226 (97.8% to 100%)
2	1	223, 224 (98.2% to 98.7%)	225, 226 (99.6% to 100%)
	2	-	224, 225, 226 (99.1% to 100%)
	3	-	225, 226 (99.6% to 100%)
	4	-	225, 226 (99.6% to 100%)
3	1	-	223, 224, 226 (98.2% to 98.7%, 100%)
	2	-	226 (100%)
	3	-	-
	4	-	225, 226 (99.6% to 100%)

Table 5. DU_{lq} for each subunit with different emitter samples and different numbers of completely clogged emitters at three times. Means followed by different letters are significantly differences (p < 0.001).

Time	Subunit	Totally Clogged Emitters (%)	DU_{lq} Computed with Various Procedures: All Emitters	Merriam and Keller (1978)	Burt (2004)	Juana et al. (2007)
0 h	1	0.0	95.5	95.2	95.7	97.6
	2	0.0	94.1	96.3	94.5	96.0
	3	0.0	96.4	97.8	96.2	98.7
	Mean	0.0	95.3 a	96.4 a	95.5 a	97.4 a
500 h	1	0.8	93.2	66.4	92.7	96.0
	2	0.2	93.4	82.1	94.5	98.5
	3	0.0	95.0	95.7	92.8	96.5
	Mean	0.3	93.8 a	81.4 a	93.3 a	97.0 a
1000 h	1	1.2	89.5	28.6	74.0	92.4
	2	1.0	88.2	0.00	85.8	92.7
	3	0.7	91.8	33.9	86.5	95.2
	Mean	1.0	89.8 a	20.8 b	82.1 a	93.4 a

of the driplines, which began to become clogged at around 500 h (table 4). Actually, only one final emitter was not completely clogged at the end of the experiment (table 4). The four driplines in subunit 2 had all their final emitters completely clogged (table 4); consequently, the DU_{lq} value was 0. When no clogged emitters were found (0 h) or just a few occurred (500 h), the DU_{lq} obtained using the Merriam and Keller procedure was not statistically different from those obtained with the other two procedures.

The Burt (2004) procedure, which also used emitters located at the dripline ends but with a much greater number (i.e., 28 emitters) than the Merriam and Keller procedure, only resulted in a smaller DU_{lq} value (82.1) at 1000 h when 1% completely clogged emitters were found than when DU_{lq} was computed with all emitters (89.8). Because the locations suggested by the Juana et al. (2007) procedure were farther from the distal positions, the DU_{lq} computed with this procedure had the greatest values, although not significantly different from the other procedures, except for the Merriam and Keller procedure at the end of the experiment.

Differences in the DU_{lq} values were assessed by computing the RMSE values (eq. 4) between each procedure and the results obtained using the discharge of all emitters in the field (table 6). In the first emitter discharge assessment, carried out within the first 20 h of operation, RMSE was low, with the Juana et al. (2007) procedure having the greatest error (2.1%). After 500 h of operation, some completely clogged emitters appeared, and the RMSE values increased slightly for Burt (2004) (from 0.3% to 1.4%) and Juana et al. (2007) (from 2.1% to 3.5%) and noticeably for Merriam and Keller (1978) (from 1.4% to 16.8%). The reason was that some completely clogged emitters were found at the positions used by the Merriam and Keller (1978) procedure (table 4). The Burt (2004) procedure also used some of the distal emitters, but only in one dripline (distal emitters are likely to have the worst contamination), and a greater number of

Table 6. Root mean square error (RMSE) between DU_{lq} obtained using all emitter discharges and the DU_{lq} computed following the different estimation procedures.

Measurement Time	N	Average Completely Clogged Emitters	RMSE for DU_{lq}: Merriam and Keller (1978)	Burt (2004)	Juana et al. (2007)
0 h	3	0.0%	1.4	0.3	2.1
500 h	3	0.3%	16.8	1.4	3.5
1000 h	3	1.0%	70.4	9.6	3.7
All data	9	0.4%	41.8	5.6	3.2

samples (28 emitters). Therefore, because the average discharges were computed using more observations (i.e., 60 emitters), the impact of a few fully clogged emitters (i.e., 0 L h^{-1} discharge) on the DU_{lq} was limited. After 1000 h of operation with reclaimed effluent, the RMSE reached its maximum values and was much greater for the Merriam and Keller (1978) procedure (70.4%) but still reasonably low for Juana et al. (3.7%). The Burt (2004) procedure increased the RMSE to 9.6% because four completely clogged emitters occurred in the fourth dripline of subunit 1, and smaller discharges were also observed in some of the additional emitters included in the distal dripline sampling. When the overall results were analyzed, lower RMSE values were found for Juana et al. (2007) (3.2%) and Burt (2004) (5.6%) than for Merriam and Keller (1978) (41.8%).

It is obvious that the sampling of emitters influences the DU_{lq} values, especially when emitters begin to clog. This can be easily seen with the low RMSE obtained using the Juana et al. (2007) procedure, which avoided selecting the distal positions in the driplines. When the last emitters in a dripline are selected and they have a greater degree of clogging, as happened in this study with the Merriam and Keller (1978) procedure, the computed DU_{lq} differs greatly from the overall DU_{lq}. However, these last emitters are probably the critical emitters where clogging can be easily detected. Different locations of clogged emitters might yield a very different DU_{lq}, although Feng et al. (2019) reported that emitter clogging also has some randomness. However, that randomness would not affect the DU_{lq} computed with all emitter discharges. Although measuring emitter discharge with more emitters, following the Burt (2004) procedure, would theoretically yield a DU_{lq} closer to its real value, the error increased when approximately 1% of the emitters were clogged. Conversely, the results were obtained in a field with low slope (0.85%). In fields with greater slope or with other system configurations, the results could have been quite different. Moreover, extended operating time, low water quality, longer driplines, and poor maintenance practices, such as lack of or inconsistent chlorination, filter backwashing, and dripline flushing, may also reduce DU_{lq} (Enciso-Medina et al., 2011).

The experiment only lasted 1000 h; if it were extended, more emitters would have likely become clogged. To assess if the various DU_{lq} estimation procedures would have had larger differences if such progression had occurred, the totally clogged emitters in subunit 3 at 500 h were extended by various percentages from the distal ends of the driplines. The locations and percentage of clogged emitters definitely affected the accuracy of the different estimation procedures, and it quickly became apparent that none of the estimation procedures was accurate when substantial clogging of the distal ends of the driplines occurred (fig. 3).

Specific procedures might be needed for assessing the field uniformity of systems when substantial clogging exists. However, when substantial clogging has occurred, it seems more likely that the field locations impacted by clogging would be remediated or replaced to ensure optimal crop production. In our case, the average emitter discharge was reduced by 11.2% during the experiment. An overall flow reduction of this magnitude may affect the ability to meet crop water needs, depending on the pumping plant characteristics and operating procedures (e.g., available daily hours of pumping).

It also should be noted that the results were obtained using PC emitters. Theoretically, the discharge for this type of emitter should not be greatly affected by dripline pressure losses; therefore, the DU_{lq} should be greater than if non-PC

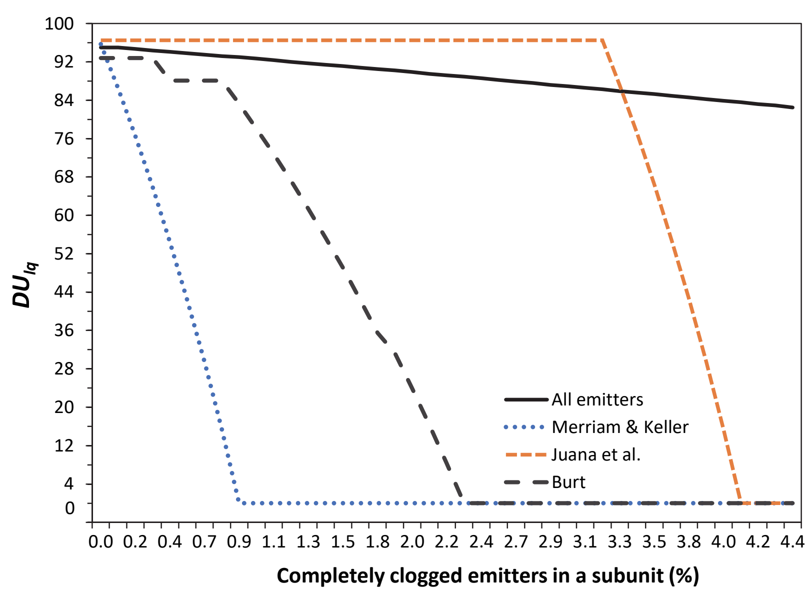

Figure 3. DU_{lq} for the entire data set for subunit 3 at 500 h as affected by an extended progression of totally clogged emitters from the distal ends of the driplines for the different calculation procedures.

emitters had been used. The effect of effluent on the clogging of PC and non-PC emitters depends on the emitter design (Pei et al., 2014), but Gamri et al. (2014) found that PC emitters were more prone to clogging due to biofilm growth that blocked the membranes of the emitters.

CONCLUSIONS

A field experiment was carried out to assess the effects of different procedures used for computing the distribution uniformity of the lower quartile (DU_{lq}). Three evaluations of field uniformity distribution separated in time (0 h, 500 h, and 1000 h of operation) were performed for three irrigation subunits that used reclaimed effluent in a field with 0.85% slope.

The emitter discharge measured using all the emitters did not follow a normal distribution at any of the measurement times. As the operating time of the subunits increased, the distribution of the emitter discharge moved further from a theoretical normal distribution (i.e., increased skewness and kurtosis) because of increased clogging. After 1000 h of operation, the average emitter discharge was reduced by 10.9%, and the average CV of emitter discharge increased by 211%.

The DU_{lq} computed with the Merriam and Keller (1978) procedure had the greatest RMSE when compared with the DU_{lq} calculated using the discharge of all the emitters in a subunit when complete clogging of less than 1% of all emitters occurred and the clogged emitters were located at the ends of the driplines. When the number of sampled emitters was greater, as in the Burt (2004) procedure, or when the sampled emitters were in locations not typically affected by clogging, as in the Juana et al. (2007) procedure, the calculated DU_{lq} more closely matched the real value. When the percentage of completely clogged emitters at the distal ends of a subunit was above 4%, the DU_{lq} calculated with any of these procedures was equal to zero and did not accurately represent the real DU_{lq}.

Nevertheless, the DU_{lq} values obtained with the different procedures may still provide information about performance issues and clogging in microirrigation systems, and therefore further observations and maintenance operations for solving these issues could be conducted. However, specific procedures may need to be developed for assessing field uniformity in microirrigation systems when substantial clogging is likely to occur, such as when using reclaimed effluent. It should be noted that this study focused on how DU_{lq} calculations are affected by the emitter sampling procedure and emitter locations when experimental conditions favor emitter clogging.

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