Using the step by step models to evaluate field application uniformity of subsurface drip irrigation systems

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Abstract. Compared to other irrigation methods, drip irrigation systems (DI) are considered one of the most efficient form of irrigation. Subsurface drip irrigation allowed reducing water losses by evaporation, runoff, and deep percolation comparing to other irrigation systems supplying water on soil surface. Field evaluation of Uniformity of water applications and its stability, however, are still a matter of controversy and deserve more investigation, since the collection of water discharged needs to excavate the soil around the emitters. Experiments carried out at the Department of Rural and Agrifood Engineering of Polytechnic University of Valencia allowed describing a methodology to assess the performance of drip irrigation through hydraulic characterizations and an emission uniformity coefficient, using the step by step models. Calculations evidenced that operating pressures on emitters ranged between 127.6 kPa and 131.7 kPa, whereas the corresponding flow rates varied from 4.00 L/h and 4.07 L/h, with an average value of 4.02 L/h. Variability in the emitters' flow rate resulted very limited due to the short length of the lateral (25.6 m). However, more attention should be paid to this for a longer field dimensions. Consequently, the value of emission uniformity coefficient was equal to 96.3%, testifying the uniform water distribution within the sub-plot.

Keywords: Field uniformity; Coefficient of variation; Flow variation; Laboratory SBS.

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Introduction

Population is in continuous increase and the amelioration of people's living standard will lead to increase in food demand in the near future. Most of this food need will be met by the irrigated agriculture. At the same time, projections predict a decrease of water input per unit irrigated area in response to water scarcity and environmental concerns region (Schultz, 2000; Chaves et al., 2007; IPCC, 2007). In that context comes the necessity of improving water use efficiency (Madramootoo and Fyles, 2010). The first step in optimizing the efficiency of any irrigation management program is to make sure that the irrigation system is well chosen and designed (Ghazouani, 2017). Irrigation scheduling and uniformity are two key factors for increasing water plant profits. Irrigation scheduling aims to determine the correct timing and amount of water, necessary for maintain root moisture within the optimal range for crop growth Irrigation uniformity, in adverse, is related to how equal water is distributed over the field area. Compared to other irrigation methods, drip irrigation systems (DI) are considered one of the most efficient form of irrigation. Subsurface drip irrigation allowed reducing water losses by evaporation, runoff, and deep percolation comparing to other irrigation systems supplying water on soil surface (Camp, 1998; Alizadeh, 2001; ASAE, 2005). According to the American Society of Agricultural and Biological Engineers (ASABE, 2007), SDI allows "*application of water below the soil surface through emitters, with discharge rates generally in the same range of the drip irrigation*". In addition, the annual replacement of system components, necessary for traditional drip irrigation systems, increases the irrigation cost and reduce the gross margin of the producer (Camp et al., 1997). In contrast, the emitters clogging by roots, soil particles, and ions disturb

the flow rate of the emitter of subsurface drip systems (Camp, 1998; Ayars et al., 1999). However, In order to achieve a satisfactory performance, any irrigation system should ensure the water distribution uniformity, that depends on friction and local losses, land slope, emitter sensitivity to pressure and temperature variations, emitter quality, as well as emitter clogging. Moreover, under subsurface drip irrigation systems, emitter flow rate can also be affected by soil properties. In particular soil topography and friction losses, among other factors, influence the relationship between flow rate, Q, and operating pressure, P:

$$Q = k\,P^x \qquad\qquad (1)$$

Where: *k* and *x* are two coefficients depending on the emitter model.

The manufacturer coefficient of variation, CV, is a measure of the variability of emitter flow rate at a certain operating pressure. This coefficient is therefore related to the manufacturing quality and it is usually determined before installation to avoid ageing effect (ASABE, 2007). However, under field condition and after use the emitters could change their performance, with unavoidable consequences on water uniformity.

A number of coefficients have been used to express field distribution uniformity. In addition to Christiansen's (1942) Coefficient (UC), the Karmeli and Keller (1975) coefficient, EU, the statistical coefficient of variation, CV, and the low quarter distribution uniformity coefficient, DU_{lq} (Kruse, 1978), have been largely used. All these coefficients reproduce the uniformity of the water distributed across a field, accounting for the variability of discharges associated to the emitter's hydraulic characteristics and possible clogging, as well as field topography. A Qualitative standard

classification, have been developed by ASAE (2005) based on manufacturer's coefficient of emitter variation (CV). ASAE (2005) reported that CV values below 10% are considered suitable and more than 20% are unacceptable. Moreover, the emitter discharge variation rate (qv) should be evaluated as a design criterion in drip irrigation systems; qv bellow 10% may be regarded as good and qv more than 20% as unacceptable (Wu and Gitlin, 1979; Camp et al., 1997).

However, field evaluation of these parameter requires measurement of emitter flow rate and pressure at selected locations throughout the field. This can be easily done for traditional DI systems where the emitters are located on the soil surface; it is much more complicated for SDI systems, because the collection of water discharged needs to excavate the soil around the emitters to be evaluated. Moreover, Sadler et al. (1995) evidenced that excavating the emitter increased the flow rate between 2.8% and 4.0%. For these reasons, models for design and evaluation of drip irrigation systems, such as the Step by Step (SBS) procedure, may be used to evaluate field application uniformity of subsurface systems (Wu and Gitlin, 1979).

The main objective of this study, is to describe laboratory procedure aiming to evaluate the performance of subsurface drip irrigation system through hydraulic characterizations and an emission uniformity coefficient and to test and its dependence on operation pressure and tape length.

Material and methods

Experiments were carried out on a drip irrigation system supposed to be implemented on four plots (treatments T1, T2, T3 and T4) in order to investigate the effects of two different water qualities and two different irrigation regimes. Treatments T1 and T2 were irrigated with good water quality, whereas treatments T3 and T4 with saline water. All investigated treatments were subjected to the same seasonal crop management, except that for irrigation doses; in particular, treatments T1 and T3 were maintained under full irrigation, in order to supply the volumes corresponding to the maximum crop evapotranspiration estimated between consecutive watering. On the other hand, treatments T2 and T4 received approximately the half of irrigation volumes provided in T1 and T3. The geometric features (pipe internal diameter, emitter spacing, diameter and length); the hydraulic characteristics, i.e. the flow rate-pressure head relationship, q(h) and the manufacturing coefficient of variation, CV, usually considered for the quantitative evaluation of the emitters' quality (Solomon, 1979), have been determined according to the Step by step models (SBS). Both the q(h) relationship and the CV value were evaluated by testing a sample of 25 emitters by following ISO 9261:2004 (ISO, 2004). The value of CV was determined as:

$$CV = \frac{\sigma}{q_m} \qquad (2)$$

where σ [L/h] is the standard deviation of the flow rates of the examined emitters' sample and q_m [L/h] is the arithmetic mean of individual emitter discharges.

Experiments were carried out at the Department of Rural and Agrifood Engineering of Polytechnic University of Valencia, by using the installation shown in Figure 1.
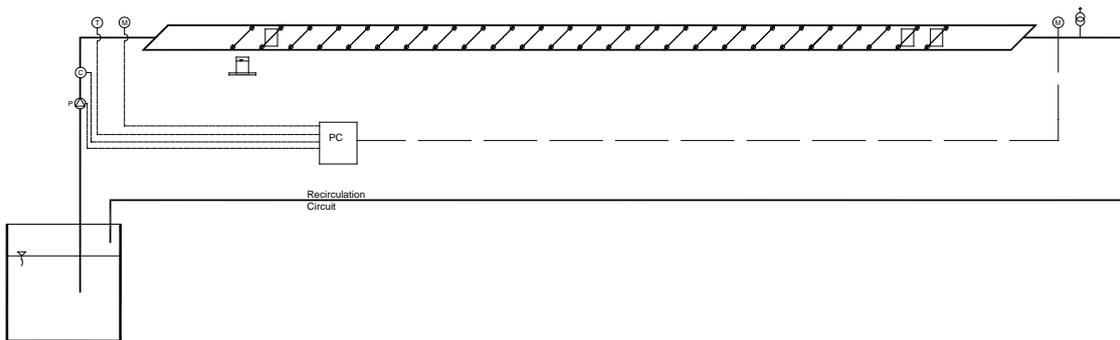
Figure 1. Images of the tested trams of drip laterals and of the test bench used for the emitters' hydraulic characterization. In the lower part is shown the schematic layout of installation.

Twenty-five trams of pipe (25 cm length), randomly selected from a 200 m long coextruded lateral and containing one emitter, were tested. Initially, the internal diameter of the pipes and the emitters were measured. The former, D_i, was measured by using ten 30 cm long pipe samples that were weighted by a precision balance before and after filling the sample with distilled water of a known temperature. The same methodology was used to measure the internal emitter diameter, D_g, whereas the emitters length, L_g, were measured by a precision Vernier caliper (Provenzano and Pumo, 2004).

All the selected trams of drip pipe were inserted between two PVC pipes having nominal diameter ND = 32 mm. Two pressure gauges (P1, P2) with a precision of 1.0 hPa and one thermometer with a precision of 0.1 °C were installed in the circuit, in order to monitor the pressure and the water temperature during the experiments. All the tests were carried out by maintaining

the water at a temperature of 23 °C ± 3 °C and by using clear water, filtered through a 150 mesh filter.

The circuit was fed and pressurized by an electrical pump fitted with a pressure control system. The test was performed after flushing the sample with clean water in order to wash the powder that could have been inside the labyrinth. After conditioning the circuit for a total of 1.0 h, according to the step by step models suggested by ISO 9261:2004 (ISO, 2004), the emitter flow rates were measured, by weight, at pressures of 49.7, 94.0, 138.1, 182.4, 226.7, 271.2 and 315.8 kPa. Individual emitter discharges were determined by weighting the volume of water flushed for 15 min inside collector containers in which load cell sensors (precision of 0.01 g) were installed. The measured water temperature allowed to account for the actual water density. All the load sensors, pressure gauge and thermometer were interfaced to a personal computer, specifically programmed in LabVIEW, for the data acquisition and the subsequent analysis. For each pressure value applied to the circuit, the standard deviation of flow rate was also evaluated in order to verify the emitter quality according to the manufacturing variation's coefficients.

Once known the dripline geometric and hydraulic characterization it was possible to evaluate the field distribution uniformity coefficient, EU [%], based on the definition proposed by Karmeli and Keller (1975):

$$EU = 100 \left[1 - 1.27 \frac{CV}{\sqrt{N}} \right] \left(\frac{Q_{min}}{Q_{avg}} \right) \qquad (3)$$

Where: CV is the emitter manufacturer's variation coefficient, N is the number of emitters per plant, Q_{min} and Q_{avg} are minimum and average emission rates in the subplot, respectively.

The step by step procedure (Provenzano and Pumo, 2004), starting from the downstream end of the last lateral and proceeding to the upstream end of the sub-plot network, allowed the evaluation of operating pressure head and the actual flow rate corresponding to each emitter, based on the field topography, the effective dripline geometry, as well as the q(h) relationship experimentally evaluated.

Results and discussion

Table 1 shows the pipe nominal diameter (ND) and the nominal flow rate as indicated by the manufacturers (Qn), the mean, μ, and standard deviation, σ, of measured pipe (Di) and emitter (Dg) internal diameters and emitter length (Lg) as well as the net spacing between emitters, S, and the value of Di/Dg ratio.

Table 1. Pipe nominal diameter, ND, nominal flow rate, Q_n, mean, μ, and the standard deviation, σ, of D_i, D_g and L_g; the values of the emitter spacing S and the ratio D_i/D_g are also indicated.

ND	Q_n	D_i		D_g		L_g		S	D_i/D_g
[mm]	[L/h]	μ [mm]	σ [mm]	μ [mm]	σ [mm]	μ [mm]	σ [mm]	[mm]	[mm]
16	4.0	11.86	0.15	11.50	0.12	68.0	1.9	332	1.031

Table 2 shows the weight of water flushed in 15 min from the tested emitters under different water pressures. The values of manufacturer coefficient variation, CV, and the average flow rates, Q_m, are also indicated at the bottom of the table. As can be observed, for a fixed pressure, the weight of discharged

volumes and therefore the emitter flow rates of different emitters were not constant due to the slight differences caused by the manufacturing process. However, considering that the coefficient of variation resulted on average equal to 2.6%, for the examined operating pressures and in line with the criterion proposed by Solomon (1979), the

emitters' quality can be classified as excellent (CV ≤ 3.0%).

Figure 2 shows the experimental values of emitters flow rate, Q [L/h], and the corresponding operating pressure, P [kPa], indicated in table 3.6, as well as the related fitting curve, having equation:

$$Q = 0.337 \, P^{0.5105} \qquad (4)$$

Table 2. Weight of water flushed in 15 min from the tested emitters under different operating pressures. The values of manufacturer coefficient variation, CV, and the average flow rates, Q_m, are also indicated at the bottom of the table.

Pressure [kPa]	99.6	49.7	94.0	138.1	182.4	226.7	271.2	315.8	359.7	359.6
Time [s]	900	900	900	900	900	900	900	900	900	900
Temperature [°C]	21.7	21.9	22.0	22.1	22.2	22.1	22.1	22.2	22.3	22.3
Emitter					Weight of emitted water					
	[g]	[g]	[g]	[g]	[g]	[g]	[g]	[g]	[g]	[g]
1	888.00	622.14	861.65	1053.08	1211.97	1353.40	1479.90	1594.50	1704.54	1705.08
2	877.54	617.72	852.66	1037.32	1197.54	1343.09	1471.74	1584.20	1696.53	1695.39
3	916.52	644.59	893.60	1082.77	1251.37	1397.37	1528.28	1651.99	1765.37	1768.13
4	892.91	631.15	866.69	1053.63	1215.18	1361.83	1491.11	1605.57	1715.16	1716.80
5	882.22	619.04	857.29	1046.69	1204.95	1343.71	1472.78	1588.72	1697.21	1695.58
6	910.04	634.60	878.59	1080.67	1243.74	1385.90	1522.20	1634.97	1753.27	1753.56
7	855.97	591.99	828.95	1017.99	1168.49	1301.18	1428.24	1536.20	1641.53	1641.08
8	884.67	616.20	860.64	1048.31	1208.24	1348.46	1472.35	1591.81	1696.42	1699.18
9	881.41	621.68	858.75	1038.24	1204.88	1341.41	1461.34	1581.31	1687.56	1688.80
10	877.46	616.81	853.13	1037.46	1199.30	1333.22	1462.08	1575.72	1683.39	1683.99
11	910.73	632.66	885.38	1086.26	1244.98	1386.92	1525.65	1643.78	1759.19	1757.18
12	841.89	588.25	816.36	999.18	1144.96	1284.99	1404.25	1513.01	1620.62	1618.86
13	872.05	608.28	843.71	1031.42	1187.40	1328.27	1453.51	1564.77	1673.98	1673.35
14	902.54	629.96	880.92	1063.13	1225.06	1375.75	1508.28	1630.44	1742.99	1745.21
15	863.13	606.00	840.39	1024.91	1183.41	1317.48	1442.93	1553.96	1664.02	1664.54
16	850.79	597.49	825.70	1013.07	1166.20	1300.32	1420.14	1528.50	1637.73	1635.81
17	851.99	595.76	826.10	1009.75	1163.53	1297.68	1422.63	1533.17	1642.34	1639.90
18	863.12	606.55	840.33	1016.52	1176.67	1311.71	1436.13	1549.84	1658.74	1659.55
19	859.40	604.67	834.46	1013.87	1171.84	1308.27	1431.68	1544.72	1652.77	1653.00
20	916.26	642.69	891.14	1091.42	1254.16	1399.19	1533.83	1655.46	1768.13	1766.48
21	905.39	631.36	875.05	1076.47	1236.55	1376.56	1509.88	1624.14	1742.29	1741.85
22	889.51	617.10	861.51	1056.33	1212.65	1356.24	1486.66	1602.33	1713.56	1710.29
23	913.32	634.08	885.19	1082.41	1247.30	1393.98	1526.23	1647.30	1759.49	1759.77
24	880.26	622.05	859.19	1040.39	1205.13	1345.76	1467.11	1585.03	1696.16	1697.19
25	859.74	602.17	834.27	1016.59	1175.85	1309.24	1437.13	1550.78	1658.66	1658.49
Average weight [g]	881.87	617.40	856.47	1044.71	1204.05	1344.08	1471.84	1586.89	1697.27	1697.16
St. Dev. [g]	22.52	15.65	22.16	27.39	30.84	34.53	38.68	42.14	44.58	44.97
CV [-]	2.55	2.54	2.59	2.62	2.56	2.57	2.63	2.66	2.63	2.65
Q_m [l/h]	3.53	2.47	3.43	4.18	4.82	5.38	5.89	6.35	6.79	6.79
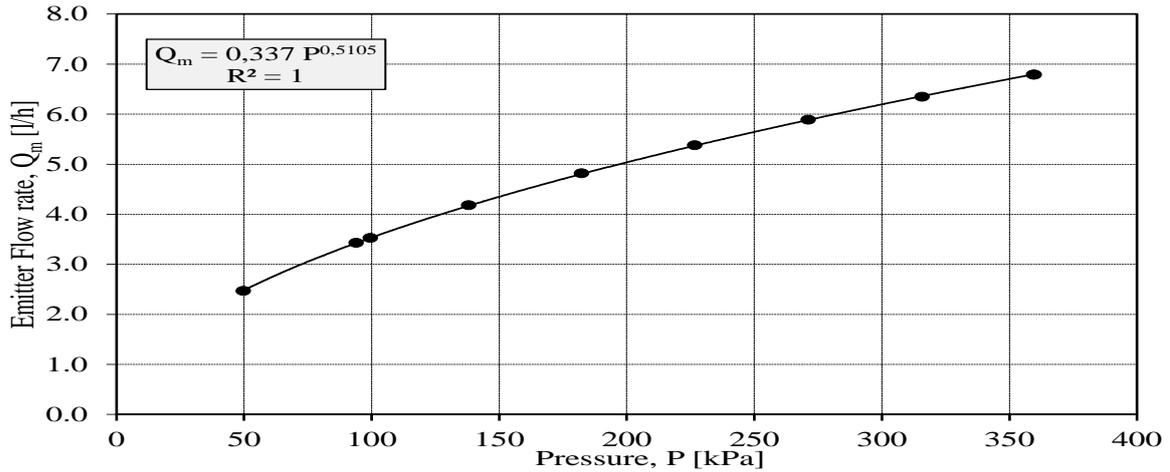
Figure 2. Flow rate as a function of operating pressure for the emitters used in the experiments.
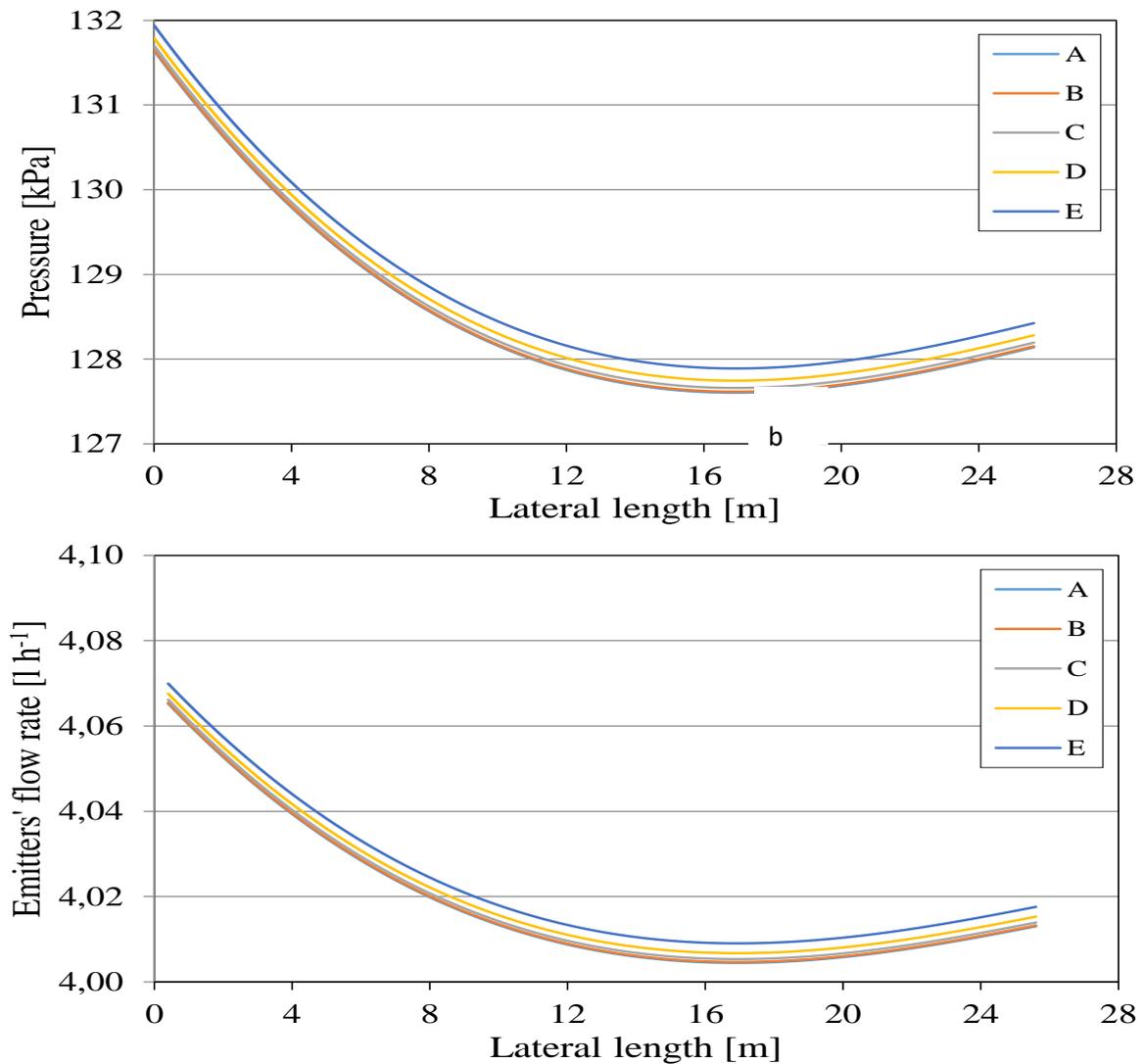
Figure 3. Operating pressures (a) and emitters flow rate (b) as a function of the lateral length. Letters in legend indicate drip laterals in the sub-plot, from the last (A) to the first (E).

Discussion

It was verified from table 2 that, the nominal flow rate of 4.0 L/h is discharged at pressure of 127.3 kPa and not at the pressure of 100 kPa as usually considered. Moreover, by increasing the operating pressure from 50 kPa to 200 kPa, the discharge values rise from 2.5 L/h to 5.0 l/h. In order to distribute the correct amount of water through the field, it is therefore very important to control operating pressures during irrigation. Karmeli and Keller (1975) emission uniformity coefficient, EU, was evaluated based on the step by step (SBS) procedure, applied on each sub-plot distribution network, consisting of five drip laterals (ND 16) and a submain pipe (ND 32). The procedure, implemented in an excel spreadsheet, allowed to take into account soil topography, dripline and submain geometric and hydraulic characteristics, as well as pipe friction losses and local losses due to the emitters' connections. Figure 3 shows the operating pressures and the corresponding emitters' flow rate (b) versus the lateral length, obtained for the five drip laterals (from the last, A to the first, E) installed in treatment T1, by assuming an operating pressure at the downstream end of last drip lateral equal to 128.1 kPa.

The performed calculations evidenced that operating pressures on emitters installed in the sub-plot (treatment T1) ranged between 127.6 kPa and 131.7 kPa, whereas the corresponding flow rates varied from 4.00 L/h and 4.07 L/h, with an average value of 4.02 L/h. The theoretical limited variability in the emitters' flow rate is due to the short length of the lateral (25.6 m) and to the small pressure losses in the laterals and in the submain pipe. Consequently, the value of emission uniformity coefficient evaluated by equation 3, equal to 96.3%, reflected the fairly uniform water distribution within the sub-plot.

Conclusion

Subsurface irrigation has been the focus of attention mainly because of its low evaporation rate and deep percolation losses. Uniformity of water applications and its stability, however, are still a matter of controversy and deserve more investigation. Experiments carried out at the Department of Rural and Agrifood Engineering of Polytechnic University of Valencia allowed to describe how to assess the performance of a drip irrigation through hydraulic characterizations and an emission uniformity coefficient, using the step by step models. The performed calculations evidenced that operating pressures on emitters ranged between 127.6 kPa and 131.7 kPa, whereas the corresponding flow rates varied from 4.00 L/h and 4.07 L/h, with an average value of 4.02 L/h. The theoretical limited variability in the emitters' flow rate is due to the short length of the lateral (25.6 m) and to the small pressure losses in the laterals and in the sub main pipe. Since, more attention should be paid to this limited variation for a longer field dimensions. Consequently, the value of emission uniformity coefficient was equal to 96.3%, reflected the fairly uniform water distribution within the sub-plot.

Conflict of interest

The authors declare that there is no conflict of interest.

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