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# Effect of flushing frequency on emitter clogging in microirrigation with effluents[1]

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## Abstract
Flushing is an important maintenance task that removes accumulated particles in microirrigation laterals that can help to reduce clogging problems. The effect of three dripline flushing frequency treatments (no flushing, one flushing at the end of each irrigation period, and a monthly flushing during the irrigation period) was studied in surface and subsurface drip irrigation systems that operated using a wastewater treatment plant effluent for three irrigation periods of 540 h each. The irrigation systems had two different emitters, one pressure compensating and the other not, both molded and welded onto the interior dripline wall, placed in laterals 87 meters long. Dripline flow of the pressure compensating emitter increased 8% over time, while in the nonpressure compensating emitter, dripline flow increased 25% in the surface driplines and decreased 3% in the subsurface driplines by the emitter clogging. Emitter clogging was affected primarily by the interactions between emitter location, emitter type, and flushing frequency treatment. The number of completely clogged emitters was affected by the interaction between irrigation system and emitter type. There was an average of 3.7% less totally clogged emitters in flushed surface driplines with the pressure-compensating emitter as compared to flushed subsurface laterals with the nonpressure compensating emitter.

**Keywords** Flushing, wastewater, surface drip irrigation, subsurface drip irrigation, plugging

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## 1. Introduction

The use of effluents in agriculture is a viable alternative in areas where water is scarce or when there is intense competition for its use. The best way to apply effluents from the public health and environmental points of view is by means of microirrigation (Bucks et al*.,* 1979). Surface drip irrigation (DI) and subsurface drip irrigation (SDI) are two types of microirrigation systems. Surface drip irrigation uses emitters and lateral lines laid on the soil surface or attached above-ground on a trellis or tree while subsurface drip irrigation emitters are buried below the soil surface. The main advantages of these drip irrigation systems are that they increase water use efficiency, minimize salinity hazard to plants, improve chemical application, decrease energy requirements and improve cultural practices (Ayars et al., 2007). Additionally, SDI systems diminish human exposure to effluents and also vandalism potential, but have a higher initial investment cost and need careful and consistent operation, maintenance and management (Lamm and Camp, 2007).

Dripline temperatures in SDI systems are lower, which may help to reduce biological and chemical clogging hazards (Lamm and Trooien, 2005). The salt concentration is reduced at the emitter in SDI because there is no evaporation face for salts to accumulate and this helps to diminish chemical clogging (Hills et al., 1989). However, Capra and Scicolone (2007) found no significant differences in clogging between DI and SDI systems.

SDI systems must have good and consistent filtration, water treatment, flushing and maintenance plans to ensure long economic life (Lamm and Camp, 2007). Filtration systems do not normally remove clay and silt particles, algae and bacteria because they are too small for typical economical filtration. These particles may travel through the filters as individual particles, but then flocculate or become attached to organic residues and eventually become large enough to clog emitters (Nakayama et al. 2007). Therefore, dripline flushing is periodically needed to remove these particles and organisms that are accumulated within the laterals (Adin and Sacks, 1991; Ravina et al., 1992).

The irrigation system should be designed so that it can be flushed properly. To be effective, flushing must be done often enough and at an appropriate velocity to dislodge and transport the accumulated sediments (Nakayama et al., 2007). A minimum flushing velocity of 0.3 m/s is recommended for microirrigation systems (ASAE, 2003). Lamm and Camp (2007) pointed out that the ASAE criterion seems appropriate for SDI in the absence of a stronger scientific reason for higher velocities. However, a flushing velocity of 0.5 to 0.6 m/s may be needed when larger particle sizes need to be removed, like when coarser filters are used (Hills and Brenes, 2001; Nakayama et al., 2007).

There is not a general agreement on what is the best flushing frequency. Several researchers have studied different flushing frequencies: daily with stored treated effluents (Ravina et al., 1997), twice per week (Tajrishy et al., 1994) and once per week (Tajrishy et al., 1994; Hills et al., 2000) with a secondary clarified effluent, every two weeks with stored effluents (Ravina et al., 1997) and with a secondary effluent (Hills and Brenes, 2001) or fortnightly and monthly with stored groundwater (Puig-Bargués et al., 2009). However, in many areas, only one flushing is carried out at the beginning and/or at the ending of irrigation season.

The objective of this study was to analyze the effect on emitter clogging of three flushing frequencies in surface (DI) and subsurface (SDI) drip irrigation systems when using a biological effluent.

## 2. Material and methods

### *2.1. Experimental set-up*

The experimental microirrigation system (Fig. 1) had two sand filters (Regaber[3], Parets del Vallès, Spain) in parallel, both filled with 175 kg of sand as a single filtration layer. After the filtration system, 48 laterals 87 m long were installed on a 0.35 ha field (approximately 38 m wide and 94 m long) with an average slope of 0.85%. Twenty four laterals were placed on the field surface (surface drip irrigation) while the other 24 were installed approximately at a depth of 25 cm (subsurface drip irrigation).

Subsurface laterals were placed in a trench prepared with an AFT65 tractor mounted trencher (AFT Trenchers Ltd, Sudbury, England). Then the trenches were carefully backfilled with the previously removed soil.

There were two dripline types, each having a different emitter type (Netafim, Tel Aviv, Israel), that were replicated four times in the experiment. The two types of emitters used (Ram 17012 (emitter 1) and Tiran 16010 (emitter 2)) had injection molded dripper construction and were welded onto the interior dripline wall. The primary emitter and lateral characteristics are shown in Table 1.

Three flushing frequency treatments were carried out: no flushing (treatment 1), only one flushing at the end of each irrigation period (treatment 2) and a monthly flushing during the irrigation period (treatment 3). For both irrigation systems (surface and subsurface), a randomized complete block of 24 driplines (Fig. 1) was used with four replications of each combination of flushing frequency treatment and emitter type. Flushing was carried out for 5 min at a velocity of 0.60 m/s. To avoid interference with the primary focus of the study, the evaluation of flushing frequency, no chemical treatments of the irrigation water were conducted to prevent emitter clogging.

An electromagnetic flowmeter was installed at the filtration system outlet, while volumetric flow accumulators with electrical pulse generators were installed at the beginning of each dripline (Fig. 1). Pressure transducers were placed in the filtration system inlet and outlet. Additional transducers were installed at the beginning, 1/3 of the length, 2/3 and lateral ending of four randomly chosen SDI laterals, for each emitter type for the most and least frequent flushing treatment. A ball valve was installed at the inlet to each dripline lateral for onsite flow control and at every lateral end for flushing.

[3] Mention of trade names is for informational purposes only and does not constitute endorsement of the product by the authors

The tertiary effluent from the wastewater treatment plant (WWTP) of Celrà (Girona, Spain), was used in the experiments. The applied water was obtained by the filtration of the effluent from a sludge process through a disc filter with a 130 μm filtration level and treatment by ultraviolet radiation, which achieved an average reduction from $1.3 \times 10^5$ cfu/ml of mesophilic aerobic bacteria to $1.5 \times 10^4$ cfu/ml. On-line measurement of pH and temperature, dissolved oxygen (DO) and turbidity at filter inlet was achieved using Endress+Hauser (Nesselwang, Germany) sensors (Orbisint CPS11D, OxyMax W COS61 and TurbiMax W CUS 31, respectively) and transmitters (CPM253, COM253 and CUM253, respectively). At the filter outlet, only dissolved oxygen and turbidity were monitored, using the same type of sensors and transmitters installed at the filter inlet. Periodically, samples of the effluents were obtained and analyzed to verify that the sensors were measuring correctly. The pH, temperature and dissolved oxygen were determined at the experimental site with a Multi 340i (WTW, Weilheim, Germany) handheld multiparameter instrument, while turbidity was measured with a HI 93703 handheld turbidity meter (Hanna Instruments, Woonsocket, RI, USA). Good correlations ($R^2 > 0.894$) were found between these measurements and the continuous measurements conducted by the different sensors. The results of effluent characterization are shown in Table 2. According to the classification proposed by Bucks et al. (1979), the effluent would constitute a minor physical clogging hazard (due to low turbidity values, which had a good correlation with total suspended solids) and a moderate chemical clogging hazard (pH above 7.0 and below 8.0). The biological clogging hazard was also moderate, as mesophilic aerobic bacteria had levels at the filter inlet between $1.0 \times 10^4$ and $5.0 \times 10^4$ cfu/ml (Bucks et al., 1979).

Flow rate, pressure, effluent physical and chemical properties and sand filter backwashings were collected every minute in a supervisory control and data acquisition system (SCADA) previously developed (Duran-Ros et al., 2008) that was modified to receive effluent characterization. The SCADA system allowed both continuous monitoring of filter and lateral performance data and irrigation scheduling. Periodically, flowmeters were manually read to compare with corresponding values from the SCADA system.

### *2.2. Operational procedure*

The experiment was conducted in three irrigation periods, each lasting 540 h. The first irrigation period took place between August 3 and December 7, 2007, although there was a break from August 24, after 107 h of irrigation, to October 4 because the treatment plant did not supply tertiary effluent. The second irrigation period was from March 11 to May 26, 2008, and the third one from June 30 to September 8, 2008. Operation time varied between 6 h to 12 h per day, with minor interruptions of a few days duration primarily due to operational problems and system maintenance. The dates and timing of the flushing events are listed in Table 3.

Sand filters were backwashed automatically for 90 s when the pressure head loss across them was higher than 50 kPa (Ravina et al., 1992). The average inlet filter pressure was approximately 460 kPa during the three irrigation periods. The effective sand media size (size opening which will pass 10% by dry weight of a representative sample of the filter material (AWWA, 2001)) was 0.47 mm and the sand uniformity coefficient (ratio of the size opening which will pass 60% of the sand to the size opening which will pass 10% (AWWA, 2001) was 1.81. At the end of the second irrigation period and after 1080 h of operation, the sand media was replaced according to the filter manufacturer instructions. The new sand that was supplied had an effective size of 0.32 mm and a uniformity coefficient of 3.17.

The average dripline inlet pressure was 175 kPa in the first irrigation period, 154 kPa in the second and 155 kPa in the third one. However, in the first 110 h of the second irrigation period the average dripine inlet pressure dropped to 108 kPa, due to a problem in the pumping system. In addition, some electrical problems during this period affected some of the volumetric flow accumulators with electrical pulse generators located at the laterals. The average head loss was 18 and 17 kPa for the driplines of emitter 1 and 2, respectively.
During the experiment, particularly during the second and third irrigation periods, water ponded at the lateral beginning due to poor drainage in this area of the field.
Herbicide was periodically applied to the soil to prevent weed growth that might have resulted in root intrusion into the SDI emitters.

At the end of the experiment, after 1620 h of irrigation, each SDI lateral was carefully extracted by manually pulling it from the soil while a chisel plow shank passed along side the dripline at an approximate distance of 2 to 3 cm. These laterals were extracted for subsequent field assessment of emitter performance.

### *2.3. Assessment of emitter performance*

Emitter performance was evaluated at the beginning of the experiment and at the end of each irrigation period for DI laterals but only at the end of the experiment for SDI laterals using the Merriam and Keller (1978) method, modified by Vermeiren and Jobling (1986). Using this method, 2 contiguous drippers were selected in 4 laterals (with the same emitter type, irrigation system and flushing treatment) at 4 locations in each emitter line (at the beginning, at 1/3 of the length, at 2/3 of the length and at the end of the emitter line). The working pressure at each location was measured by means of a Leo 2 (Keller, Winterthur, Switzerland) digital manometer (± 0.07% accuracy) that was placed in a pressure reading socket (Ein-tal, Or-Akiva, Israel). The water delivered for each emitter selected was collected for 5 min to measure its discharge. At each evaluation period, the relative emitter discharge, $q_r$, expressed as a percentage was calculated using the following equation:

$$q_r = \left(\frac{q}{q_n}\right) \cdot 100 \quad (1)$$

where $q$ is the field measured emitter discharge (L/h) and $q_n$ is the nominal design emitter discharge (L/h) for new unused laterals. In the nonpressure-compensating emitters, discharge was normalized to the design pressure (100 kPa) using the manufacturer's emitter exponent (Table 1). Thus, it was possible to compare flow rates without the differences caused by the working pressure at each different dripline and distance from the inlet. This same procedure was used for computing the lateral flow rate of nonpressure-compensating emitter.
The distribution uniformity ($DU_{lq}$) (Keller and Karmeli, 1974) was also determined by means of:

$$DU_{lq} = \left(\frac{q_{25}}{\bar{q}}\right) \cdot 100 \quad (2)$$

being $q_{25}$ the average discharge of the 25% of the emitters with the lowest flow rate (L/h) and $\bar{q}$ the average discharge of all the emitters tested (L/h).
Pressure uniformity ($U_{plq}$) (Bliesner, 1976) was computed as:

$$U_{plq} = \left(\frac{p_{25}}{\bar{p}}\right)^x \cdot 100 \quad (3)$$

where $p_{25}$ is the average pressure of 25% of the emitters with the lowest pressure (kPa), $\bar{p}$ is the average pressure of all the tested emitters (kPa) and $x$ is the emitter flow exponent. Additionally, at every evaluation of emitter discharge, the number of totally clogged emitters of each dripline was also determined.

### *2.4. Observation of the clogging of the emitters*

After all the experimental measurements were completed, some lateral sections and emitters were analyzed for visual evidence of clogging. Clogged emitters were inspected externally and then cut open for internal inspection.

### *2.5. Statistical analyses*

Statistical analyses were carried out using the GLM procedure of the SAS statistical package (SAS Institute, Cary, NC, USA). The model used for analyzing emitter performance included as fixed effects the irrigation system, emitter, flushing frequency treatment and location along the lateral and the double interactions between them, and the replications as error term. For studying the number of totally clogged emitters, the model included as fixed effects the irrigation system, emitter, flushing frequency treatment and the double interactions between them, and replications as the error term. Tukey's pairwise comparison was used to identify means that were different at probabilities of 0.05 or less.

## 3. Results and discussion

### *3.1. Sand media filter performance*

The sand filter achieved a turbidity removal efficiency for the effluent between 61% (irrigation periods 1 and 2) and 71% (period 3). These turbidity removal efficiencies lowered the physical clogging risks and were similar to those observed with a sand media filter with effective sizes of 0.40 and 0.27 mm working with similar effluents (Duran-Ros et al., 2009). The increase in dissolved oxygen at the filter outlet [6.23% (season 1), 0.47% (season 2) and 26.56% (season 3)] indicate that some reduction of organic contaminants was achieved through filtration. The presence of less organic material after the sand media filters was also observed by Tajrishy et al. (1994) and could explain the lower fouling of emitters protected by this type of filter (Duran-Ros et al., 2009). The greater reduction in turbidity and increased dissolved oxygen achieved in the third irrigation period could be related to the smaller effective sand media size used in the third season (Ives, 1980).

The number of sand filter backwashings was 117 during the first irrigation period and 306 during the second one. This increase was primarily due to the sand media clogging by trapped particles that were observed at the end of the second irrigation period. The manufacturer indicated that the sand media should be replaced after 1000 h of operation. In the third irrigation period, the number of backwashings increased to 503 due to, first, the smaller effective sand media size and, second to some treatment plant discharge events having greater solids load in the effluent.

Although the regulated inlet pressures were similar between irrigation periods there was a steady increase in the seasonal water applications, 6005, 6087, and 6407 $m^3$ over seasons 1 to 3, respectively, which is a 7% increment over the entire course of the experiment.

### *3.2. Emitter performance*

Pressure uniformity values (Table 4) were greater than 97% for both the DI and SDI systems and for all treatments, meaning that pressure distribution along the lateral was very uniform. Since the emitter manufacturing coefficient of variation was low, discharge reductions can primarily be explained by emitter clogging. At the end of the experiment, $DU_{lq}$ (Table 4) was smaller in SDI units for both emitter types. Soil hydraulic properties can affect the discharge from a subsurface emitter, besides the manufacturer's variability, dripline pressure differences and clogging. When the soil is variable there is a corresponding variation in emitter uniformity (Warrick and Shani, 1996). Thus, the smaller $DU_{lq}$ in SDI systems could be partly related with soil heterogeneity, which was the condition of the present experiment. Camp et al. (1997), after 8 years of operation, found smaller $DU_{lq}$ in SDI than in DI emitters due to emitter clogging in SDI system caused by soil particles that entered during the installation process. When there is no emitter clogging, $DU_{lq}$ of DI and SDI systems are similar (Camp et al., 1997; Capra and Scicolone, 2007).

Distribution uniformity tended to decrease through the experiment in the DI system, especially in the not flushed treatment. Greater $DU_{lq}$ was achieved with more intensive flushing frequency, except with emitter 1 for the DI system. In a 1680 h laboratory experiment with effluents, Liu and Huang (2009) found that the $DU_{lq}$ of a pressure compensating emitter increased by 5% after a single flushing carried out at the end of the experiment. However, this performance of a pressure compensating emitter was not found in our experiment.

The dripline flow rate of emitters 1 and 2, respectively, through the experiment is depicted in Figs. 2 and 3. Emitter 1 dripline flow rate increased during the experiment for both DI and SDI systems. Previous studies have shown in some cases that pressure compensating emitters may exhibit an increase in flow rate possibly as a result of degradation of the elastic membrane or due to effluent particles getting trapped between elastic parts (Cararo, et al., 2006; Trooien and Hills, 2007; Duran-Ros et al., 2009). Emitter 2 dripline flow rates exhibited a different performance in DI and SDI after 320 h, increasing the dripline flow rate in DI and decreasing it in SDI. At the beginning of the second irrigation season, as the dripline inlet pressure was smaller, as it has been discussed earlier, dripline flow rate of this nonpressure compensating emitter was smaller. Once the dripline inlet pressure was recovered, the dripline flow differences between DI and SDI still continued and tended to increase over time. Reduction in SDI laterals is related to emitter clogging, as it will be analyzed later. The higher dripline flow rates in DI system, especially in the third season, are probably due to observed but unexplained emitter failures resulting in a flow increase, as no other leaks due to mechanical or rodent damage were detected in the surface laterals.

As $DU_{lq}$ results did not allow a statistical analysis to determine the causes, the parameters and interactions that affect the relative emitter discharge ($q_r$) were studied. Results (Table 5) show that, at the end of the experiment, a significant effect of the irrigation system and the interactions between emitter and emitter location and flushing treatment and emitter location was found. Both significant interactions are being studied individually in the next two sections.

#### *3.2.1. Effect of emitter and location*

The relative emitter discharge ($q_r$) with regard to emitter type and its location along the lateral after three irrigation periods is shown in Fig. 4. At the end of the experiment, emitter 1 (pressure compensating) had significantly greater discharge than emitter 2 (nonpressure compensating) at the lateral beginning and ending, but not at any other location. Discharge of emitter 1 was not different among locations, but emitter 2 behaved differently with the discharge at the end of the lateral significantly different from those at 1/3 and 2/3 of the total dripline length. However, emitter 2 discharges were similar at the beginning and end of the lateral. Some emitters located at the beginning of the dripline were also clogged. This may be due to the ponding that was discussed earlier.

Several studies have shown a greater clogging of emitters located at the end of the laterals (Adin and Sacks, 1991; Ravina et al., 1992, 1997; Trooien et al., 2000; Duran-Ros et al., 2009; Puig-Bargués et al., 2009), attributable to the lower velocity at this point, which favors particle settling (Shannon et al., 1982). Proper flushing can reduce emitter clogging at this location because it can remove sediments from the dripline. Puig-Bargués et al. (2009) found that sediment deposition within the SDI dripline was nearly 3 times smaller when flushing was performed.

#### *3.2.2. Effect of flushing frequency treatment and emitter location*

The relative emitter discharge at the end of the experiment depended also on the interaction between flushing treatment and emitter location (Fig. 5). No differences in relative emitter discharge with location occurred when laterals were flushed. Emitters within nonflushed driplines located near the end of the lateral had significantly smaller discharge than those at other locations or those that had been flushed. No significant differences were observed between the two flushing frequencies. Similarly, Ravina et al. (1997) did not find differences in emitter clogging when flushing the drip laterals daily or every two weeks. Puig-Bargués et al. (2009) did not find a consistant effect of a fortnight and month flushing frequency for most of the flushing velocities that they analyzed. Hills et al. (2000) found that flushing twice a month at a 2 m/s velocity rather than one weekly flushing at a smaller velocity prevented a reduction in pipe cross-sectional area but did not affect biofilm thickness in the pipes. According to our results, the two studied flushing frequencies (monthly and at the end of the irrigation period) seemed to be sufficient to remove the accumulation of sediments in the lateral. However, more frequent flushing did result in a greater $DU_{lq}$. Therefore, it is important to flush laterals periodically before the emitters became completely clogged because reclamation of partially clogged emitters is more successful (Ravina et al, 1992; Liu and Huang, 2009).

### *3.3. Analysis of completely clogged emitters*

There were only a small number of completely clogged emitters with the greatest amounts (3.7 to 4.5%) for emitter 2 with SDI (Table 6). However, it should be pointed out that the partial clogging is more frequent than the total clogging (Ravina et al., 1992). The factors that statistically affected the number of completely clogged emitters were irrigation system, emitter type and the interaction between these two factors (Table 7). Results from the interaction analysis (Fig. 6) revealed that emitter 2 with SDI had significantly more totally clogged emitters than any other combination of emitter and irrigation system. This agreed with the reduction in dripline rate observed after the first irrigation period for the SDI laterals of the emitter 2 (Fig. 3). Emitter discharge of SDI can also decrease as a result of positive pressure in the soil water matrix creating a backpressure at the emitter orifice (Warrick and Shani, 1996; Gil et al., 2008). Warrick and Shani (1996) indicated that pressure-compensating emitters can mitigate the reduction of the discharge in comparison with noncompensating emitters. This backpressure phenomenon may explain the reduction in emitter discharge for the noncompensating emitters when used in SDI rather than in DI (Fig. 3). Additionally, emitter 2 had an approximately 13% smaller nominal discharge than emitter 1 (Table 1) and this may have led to greater clogging as has been reported in other studies (Ravina et al., 1997; Trooien et al., 2000).

Dissection of some of the totally clogged emitters revealed that biofilm formation was the primary problem in the DI emitters. However, this biofilm problem was exacerbated in the SDI emitters because external soil particles became stuck in the biofilm at the emitter outlet leading to increased clogging. It is suspected the source of these soil particles was backsiphoning of water that caused soil ingestion through the emitter when the system was shutdown (Lamm and Camp, 2007). Mucous microbial substances have been found to be the main factor of emitter clogging when working with reclaimed effluents (Adin and Sacks, 1991; Ravina et al., 1997). Biofilm removal by flushing is made difficult by its low specific gravity and high adhesive characteristics. Installation of air/vacuum relief valves at the high elevation points can help prevent soil ingestion in SDI (Lamm and Camp, 2007). These devices were not installed in the irrigation system because we did not anticipate soil ingestion would be a problem for our shallow depth and for the topography of the field site. The presence of roots was observed only in two tested emitters. However, root intrusion from some weeds that grew in the last phase of the third irrigation period did not cause complete clogging, neither blocking the emitter outlet nor the emitter labyrinth. Effluent chlorination has been found to be effective in reducing clogging caused by biofilm growth (Tajrishy et al., 1994; Ravina et al., 1997). Other chemical treatments such as acidification can be also used for increasing chlorination effectiveness (Nakayama et al., 2007) and for reducing root intrusion (Choi and Suarez-Rey, 2004) when it is needed.

## 4. Conclusions

The clogging of two different emitters, one pressure compensating and the other not, working during three irrigation periods of 540 h each with a wastewater treatment plant effluent that presented a minor physical clogging hazard, but moderate chemical and biological clogging hazards, was affected by the interactions between emitter type and emitter location, and flushing frequency treatment and emitter location.

Distribution uniformity at the end of the experiment was less without flushing and subsurface drip irrigation, being 54% and 24% for the pressure and nonpressure compensating emitters, respectively. Average distribution uniformity for flushed laterals was 90% and 84% with pressure compensating emitter in surface and subsurface drip irrigation, respectively, and 91% and 58% with nonpressure compensating emitter in surface and subsurface irrigation units.
Dripline flow of the pressure compensating emitter increased 8% over time in surface and subsurface drip irrigation, but in the nonpressure compensating emitter, dripline flow increased 25% in the surface driplines and decreased 3% in the subsurface driplines as more emitters became clogged in the buried laterals.

Emitter discharge of the pressure compensating emitter did not vary along the lateral significantly. However, in the nonpressure compensating emitter, average emitter discharge was smaller at the beginning and at the end of the laterals, where more totally clogged emitters were found. Emitter clogging was greater when no dripline flushing was carried out. However, no significant differences were observed between flushing intervals carried out at a velocity of 0.6 m/s.

The pressure compensating emitter performed similarly in surface and subsurface drip irrigation systems, but the nonpressure compensating emitter was more prone to be clogged when it was used with subsurface drip irrigation with an average of 4% of emitters completely clogged. The main cause of clogging was biofilm formation. In the subsurface drip irrigation system without an air/vacuum relief valve soil ingestion by backsiphoning was also observed in completely clogged emitters. Flushing was not an effective means of removing ingested soil particles that became stuck in the biofilm. It is possible this problem may have been alleviated with chemical treatment that was not a part of the scope of this study.

Based on these findings, the tested pressure compensating emitter is recommended over the nonpressure one when applying municipal tertiary effluent. We also recommend that an air/vacuum relief valve be used for subsurface drip irrigation to avoid ingestion of soil particles due to back siphoning. Flushing at a flushing velocity of 0.6 m/s was adequate when it was performed monthly or only at the end of the irrigation season.

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Table 1. Main emitter and dripline characteristics, according to manufacturer's specifications.

| Characteristic | Emitter 1 | Emitter 2 |
|---|---|---|
| Nominal flow rate (L/h) | 2.3 | 2.0 |
| Nominal pressure (kPa) | 50-400 | 100 |
| Maximum operating pressure (kPa) | 400 | 350 |
| External diameter (mm) | 17.0 | 16.1 |
| Distance between emitters (m) | 1.00 | 1.00 |
| Flow exponent x | 0.05 | 0.46 |
| Pressure compensation | Yes | No |
| Manufacturer variation coefficient | < 3% | < 3% |
| Water passage width (mm) | 1.15 | 0.76 |
| Water passage depth (mm) | 0.95 | 1.08 |
| Water sectional area ($mm^2$) | 1.09 | 0.82 |
| Water passage length (mm) | 22.0 | 75.0 |
| Water passage filtering area ($mm^2$) | 8.0 | 70.0 |

Table 2. Mean values and standard deviation of effluent physical and chemical parameters at filter inlet and outlet.

| Parameter | | Irrigation period | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Filter inlet | Temperature (ºC) | 21.25 ± 3.52 | 19.64 ± 1.94 | 27.20 ± 1.20 |
| | pH | 7.33 ± 0.09 | 7.97 ± 0.26 | 7.46 ± 0.16 |
| | DO (mg/l) | 3.96 ± 0.80 | 3.54 ± 0.92 | 2.50 ± 0.41 |
| | Turbidity (FTU) | 10.33 ± 10.50 | 9.08 ± 9.88 | 8.06 ± 8.51 |
| Filter outlet | DO (mg/l) | 4.16 ± 0.83 | 3.57 ± 0.98 | 3.13 ± 0.48 |
| | Turbidity (FTU) | 3.40 ± 2.83 | 2.87 ± 3.66 | 2.02 ± 1.92 |

DO: dissolved oxygen; FTU: formazine turbidity unit

Table 3. Dates and accumulated irrigation time for when flushing events were carried out.

| Irrigation period | Treatment | Date | Irrigation time (h) |
|---|---|---|---|
| First | Monthly flushing | October 5, 2007 | 107 |
| | Monthly flushing | November 2, 2007 | 307 |
| | Monthly flushing/One flushing | December 7, 2007 | 540 |
| Second | Monthly flushing | April 10, 2008 | 753 |
| | Monthly flushing | May 15, 2008 | 995 |
| | Monthly flushing/One flushing | June 26, 2008 | 1080 |
| Third | Monthly flushing | August 4, 2008 | 1339 |
| | Monthly flushing/One flushing | September 8, 2008 | 1620 |

Table 4. Pressure uniformity ($U_{plq}$) and distribution uniformity ($DU_{lq}$) for each emitter type in the surface and subsurface irrigation units at the end of the irrigation periods. In subsurface drip irrigation, $U_{plq}$ and $DU_{lq}$ only was determined at the end of the experiment.

| Emitter type | Flushing frequency | Surface | | | | | | | | Subsurface | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 h | | 540 h | | 1080 h | | 1620 h | | 1620 h | |
| | | $U_{plq}$ | $DU_{lq}$ | $U_{plq}$ | $DU_{lq}$ | $U_{plq}$ | $DU_{lq}$ | $U_{plq}$ | $DU_{lq}$ | $U_{plq}$ | $DU_{lq}$ |
| 1 | No flushing | 99.8 | 95.1 | 99.9 | 94.2 | 99.8 | 83.2 | 99.8 | 76.0 | 99.7 | 54.0 |
| | Seasonal flushing[1] | 99.8 | 94.3 | 99.9 | 93.0 | 99.8 | 91.7 | 99.6 | 95.1 | 99.7 | 80.1 |
| | Monthly flushing | 99.8 | 94.3 | 99.9 | 96.0 | 99.8 | 94.0 | 99.8 | 84.5 | 99.7 | 87.7 |
| 2 | No flushing | 98.5 | 96.5 | 98.8 | 96.3 | 98.1 | 86.2 | 97.9 | 67.8 | 97.3 | 24.3 |
| | Seasonal flushing[1] | 98.0 | 97.0 | 98.8 | 96.3 | 97.9 | 96.5 | 97.9 | 87.1 | 97.6 | 47.0 |
| | Monthly flushing | 98.3 | 95.1 | 98.6 | 95.5 | 98.1 | 89.9 | 98.0 | 93.9 | 97.5 | 69.4 |

[1] A single flushing event was conducted at the end of each irrigation period.

Table 5. Significance level (P-value) of the statistical model and of each factor and interaction for explaining the relative emitter discharge ($q_r$) variability at the end of the experiment (1620 h of irrigation).

| | P-value |
|---|---|
| Model | *** |
| Irrigation system | * |
| Emitter type | *** |
| Flushing frequency | ** |
| Emitter location | * |
| Irrigation system x emitter type | n.s. |
| Irrigation system x flushing frequency | n.s. |
| Irrigation system x emitter location | n.s. |
| Emitter type x flushing frequency | n.s. |
| Emitter type x emitter location | * |
| Flushing frequency x emitter location | * |

n.s.: not significant, P>0.05, $^{*}P$<0.05, $^{**}P$<0.01, $^{***}P$<0.001.

Table 6. Average and standard deviation of the percentage of completely clogged emitters by emitter, irrigation system and flushing frequency at the end of the experiment.

| Emitter type | Flushing frequency | Completely clogged emitters (%) | |
|---|---|---|---|
| | | Surface drip irrigation | Subsurface drip irrigation |
| 1 | No flushing | 0.3 ± 0.5 | 1.4 ± 1.7 |
| | One flushing | 0.8 ± 1.0 | 0.3 ± 0.5 |
| | Monthly flushing | 0.0 ± 0.0 | 0.3 ± 0.5 |
| 2 | No flushing | 1.3 ± 1.0 | 4.5 ± 1.6 |
| | One flushing | 0.8 ± 1.0 | 3.7 ± 3.1 |
| | Monthly flushing | 0.5 ± 0.6 | 4.5 ± 1.0 |

Table 7. Significance level (P-value) of the statistical model and of each factor and interaction for explaining completely clogged emitter variability at the end of the experiment (1620 h of irrigation).

| | P-value |
|---|---|
| Model | *** |
| Irrigation system | ** |
| Emitter type | *** |
| Flushing treatment | n.s. |
| Irrigation system x emitter type | ** |
| Irrigation system x flushing treatment | n.s. |
| Emitter type x flushing treatment | n.s. |

n.s.: not significant, P>0.05, $^{**}P$<0.01, $^{***}P$<0.001.

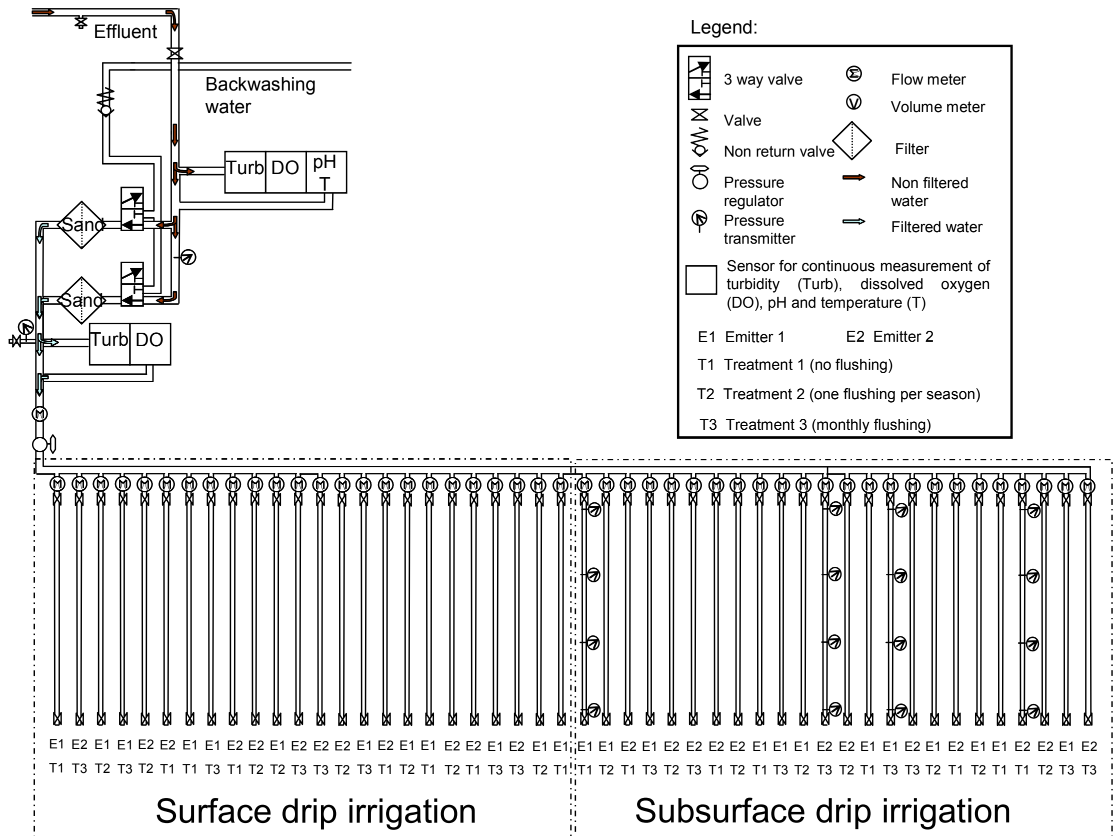


Fig. 1. Hydraulic diagram of the microirrigation system and location of monitoring and control equipment.

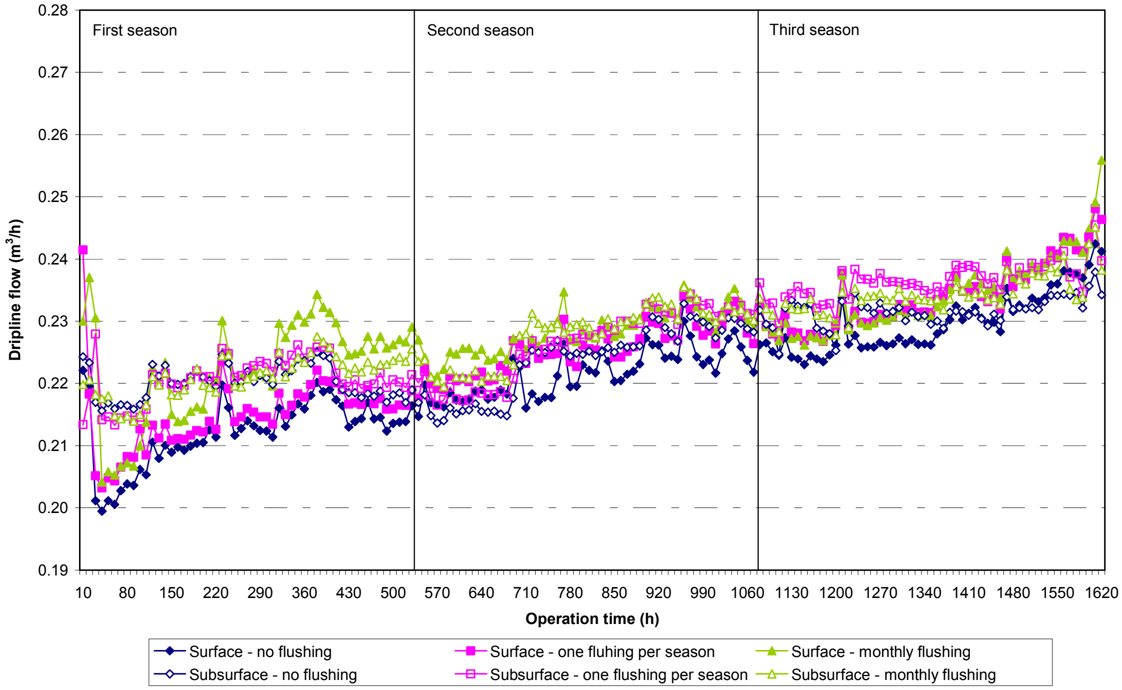


Fig. 2. Average emitter 1 lateral flow rate for every 10 h of experiment.

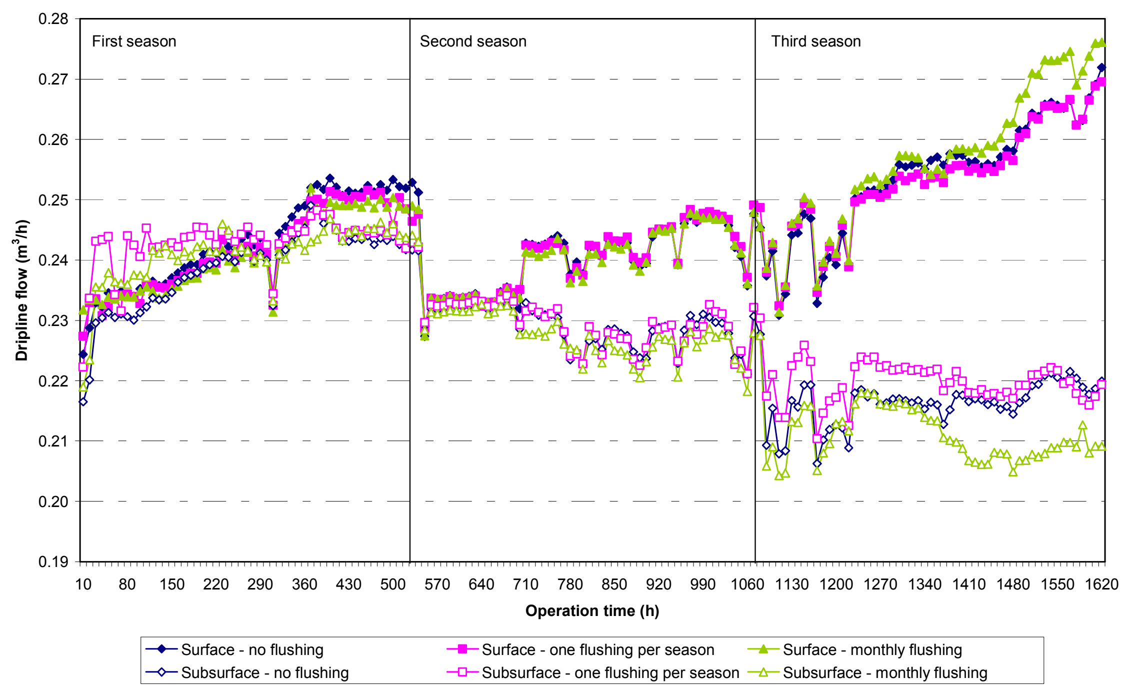


Fig. 3. Average emitter 2 lateral flow rate for every 10 h of experiment. Dotted lines show a period where the system was operating but the data was missed as the instrumentation was not working properly.

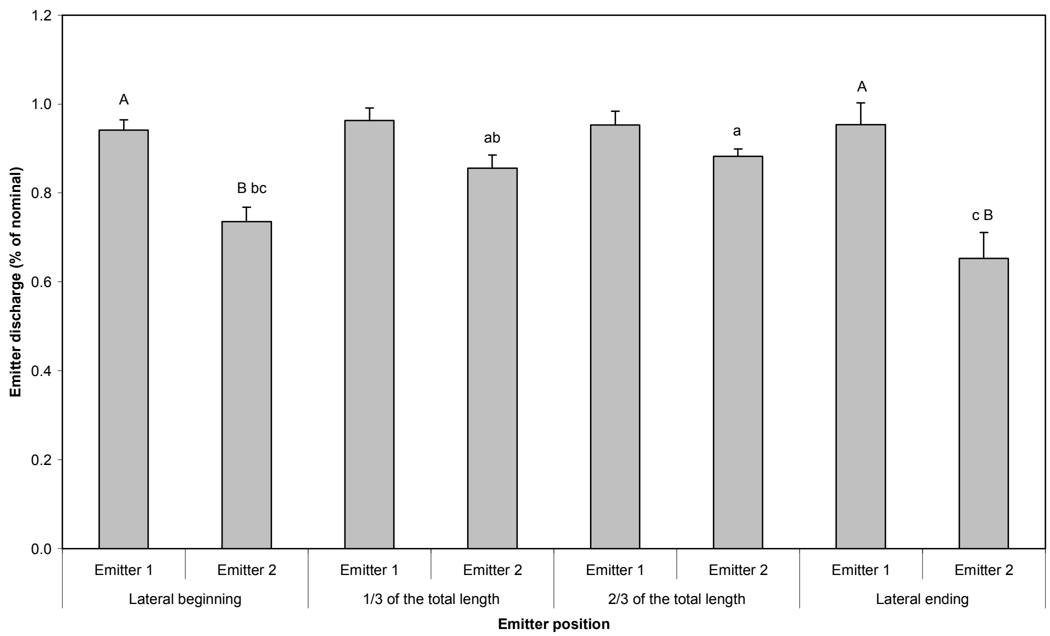


Fig. 4. Average relative emitter discharge and standard error after 1620 h for Emitter 1 (pressure compensating) and Emitter 2 (nonpressure compensating) for the different locations. For each emitter, different lowercase letters mean significant differences (P<0.05) among sampling locations. For each emitter location, different uppercase letters mean significant differences (P<0.05) among emitters.

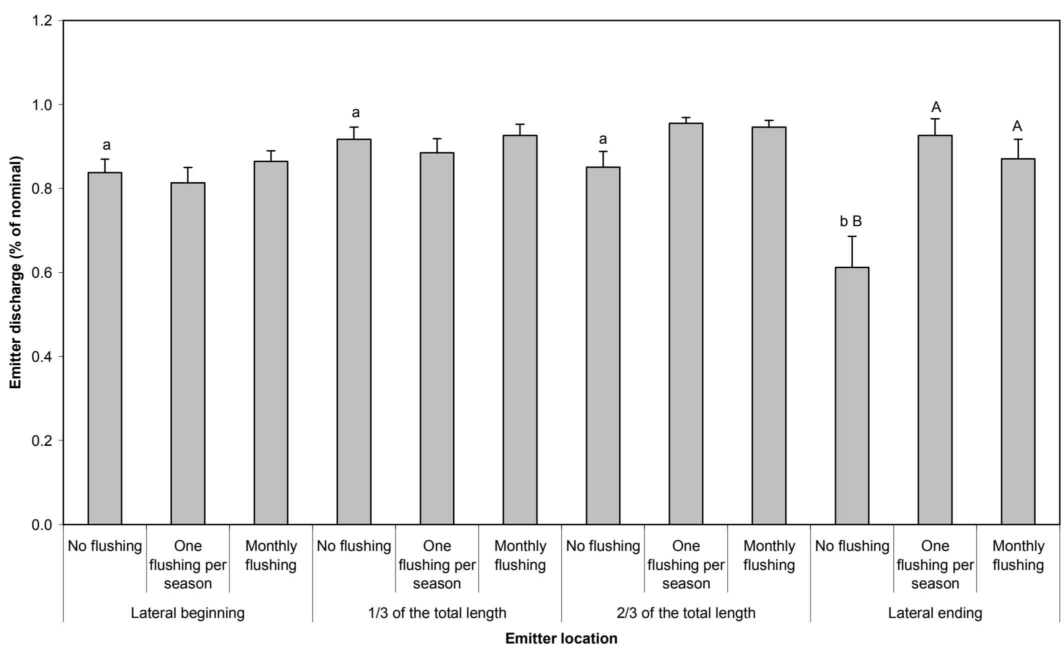


Fig. 5. Average relative emitter discharge and standard error after 1620 h for the three flushing frequency treatments for the different locations. For each flushing frequency treatment, different lowercase letters mean significant differences (P<0.05) among sampling locations. For each emitter location, different uppercase letters mean significant differences (P<0.05) among treatments.

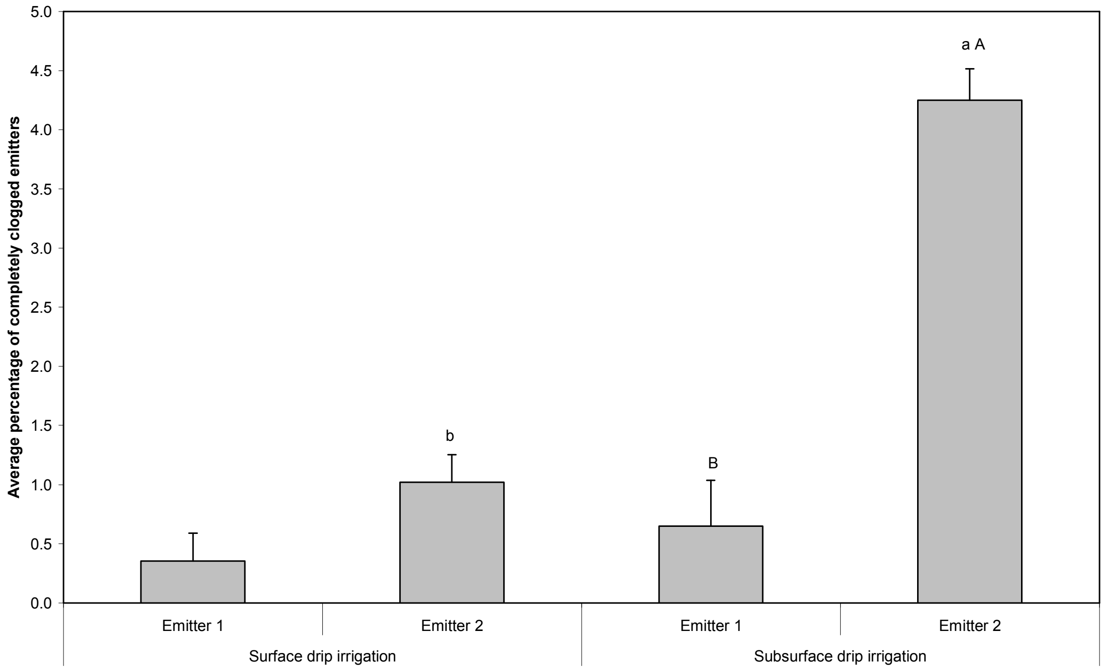


Fig. 6. Average percentage of totally clogged emitters and standard error at the end of the experiment. For each emitter, different lowercase letters mean significant differences ($P<0.05$) among irrigation system. For each irrigation system, different uppercase letters mean significant differences ($P<0.05$) among emitters.