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Influence of Flushing Velocity and Flushing Frequency on the Service Life of Labyrinth-Channel Emitters

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Abstract: Dripline flushing is an effective way to relieve emitter clogging and extend the longevity of drip irrigation systems. This laboratory study was conducted at Kunming University of Science and Technology to evaluate the effect of three targeted flushing velocities (0.3, 0.6, and 0.9 m/s) and four flushing frequencies (no flushing, flushing daily, and flushing every three or five days) on the emitter's service life and the particle size distribution of the sediment discharged from emitters and trapped in an emitter channel. The gradation of particle size was analyzed by a laser particle size analyzer. The experiment results suggested that flushing velocity and flushing frequency had a significant effect on the service life of emitters, and the emitter's service life was extended by 30.40% on average under nine different flushing treatments. Flushing can effectively reduce the accumulation of sediments in the dripline and decrease the probability of coarse particles flowing into emitters and fine particles aggregating and cementing in the labyrinth channel, thus relieving the emitter clogging. Therefore, dripline flushing can effectively slow down clogging in muddy water drip irrigation system. The recommended flushing velocity should be set at 0.6 m/s, and the flushing intervals should be shortened.

Keywords: clogging; drip irrigation; flushing; particle size distribution; sediments

1. Introduction

Dripline flushing is a necessary maintenance practice for micro-irrigation systems. It removes particles that are not strained by the micro-irrigation system filters and that accumulate in the driplines [1,2]. Physical clogging caused by solid particles is considered the most common emitter clogging category of emitters [3–5]. For drip irrigation systems in the Yellow River irrigation areas of Ningxia and Inner Mongolia, the average sediment concentration in the water abstracted from the Yellow River reaches 35 kg/m^3. A large quantity of sand enters into drip irrigation systems and results in emitter clogging even after deposition and prefiltration treatment measures are taken [6]. Therefore, flushing is required to ensure a long economic service life of drip irrigation systems [7]. On the other hand, numerical simulations on shallow water flows and river flushing have been carried out by Peng et al. [8–14].

In order to achieve an optimal flushing effect, drip irrigation systems should be designed properly. Flushing must be done often enough and at an appropriate velocity to dislodge and remove the accumulated sediments [15]. A minimum flushing velocity of 0.3 m/s was recommended by the

American Society of Agricultural and Biological Engineers Engineering Practice, EP-405 [16], but some researchers have advised that a flushing velocity of 0.5–0.6 m/s is necessary when larger particles need to be discharged; for example, it is useful when coarser filters are used in drip irrigation systems [17,18]. In a 30-day field study in which the target flushing velocities were ranged from 0.23 to 0.61 m/s, Puig-Bargués et al. [18] did not find remarkable effects of flushing velocity on the emitter discharge. However, the higher the flushing velocities were set, the more solids were removed from the laterals. Increasing the velocity of flushing may need more costly system designs (e.g., larger supply pipe main, higher pumping requirements, reduced zone sizes) and labor requirements for flushing in irrigation systems should be increased [14].

Different studies explored different flushing frequencies: daily [19], weekly [20], every two weeks [17,21], and monthly [18]. Li et al. [21] claimed that emitter clogging was minimized in cases of biweekly flushing. However, Puig-Bargués et al. [22] reported no obvious differences between flushing frequencies at a velocity of 0.6 m/s, and emitter clogging was primarily affected by the interactions between emitter type, emitter location, and frequency of flushing. Thus, a general agreement on the optimum flushing frequency is lacking at this time, and related studies on flushing frequency and flushing velocity are scarce.

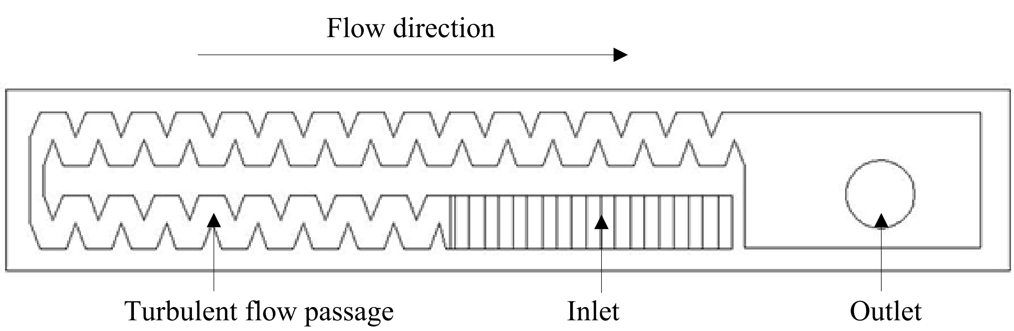
Therefore, the objective of this study was to analyze the influence of three flushing velocities and four flushing frequencies on emitter clogging in drip irrigation systems when using muddy water with full tests. Additionally, particle size distributions of the discharged sediments and residual sediments in the emitter were investigated to determine appropriate flushing schemes to extend the service life of drip irrigation systems.

2. Materials and Methods

2.1. Emitter Characteristics

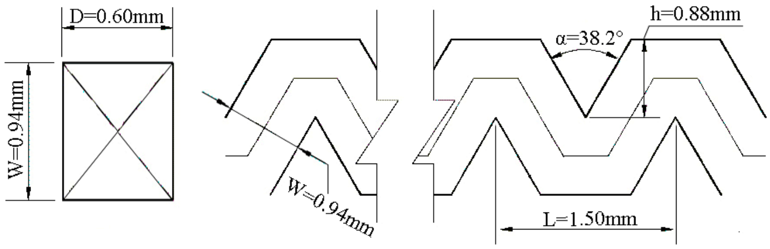
The drip tape with non-pressure-compensating emitter manufactured by Dayu Water Conservation Ltd. in Jiuquan City, Gansu Province, China, which is widely used in agricultural irrigation, was applied in the experiments. Its external diameter was 16 mm, and the thickness of the wall was 0.40 mm. Figure 1 presents the structure of the labyrinth-channel emitter. The working pressure was 0.1 MPa. The rated discharge (q) was 1.37 L/h. The flow path had a width (W) of 0.94 mm, length (S) of 37.8 mm, and depth (D) of 0.60 mm. The sectional area (A) was 0.56 mm^2. The angle between the bevel edge and baseline was 38.2°. Space width (L) and height (H) of the tooth were 1.50 and 0.88 mm, respectively. The manufacturing variation of the emitter was 0.028. The flow exponent (x) was 0.49, and the discharge coefficient (k) was 1.12.

The test driplines were cut randomly from the same roll of irrigation drip tapes. The emitter's discharge was measured using pressures of 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.08, and 0.10 MPa to calculate the discharge coefficient and flow exponent.



(**a**)

Figure 1. *Cont.*



(b)

Figure 1. Emitter used in drip tape. (**a**) Labyrinth-channel emitter; (**b**) parameters of the flow path in the emitters. W, tooth space width; D, depth; α, angle of the bevel edge and baseline; L, tooth space width; h, tooth height.

2.2. Experimental Setup

Figure 2 shows that clean water was stored in a 100-L tank and muddy water was stored in a 150-L tank. Each was equipped with a 1.8-kW submersible pump with a 42-m rated head and 1.8-m^3/h rated discharge to provide the working pressure. The pressure adjustment valve and manometer I were installed on the three parallel tubes, which were connected to the submerged pump in the clean water tank, to adjust the different targeted flushing velocities. Manometer II was used to monitor the irrigation pressure. The pressure in manometer I and manometer II was 0.06 and 0.25 MPa, respectively, and their precision was 0.25%. A test platform (1.5 m in width, 4.8 m in length, and 1.0 m in height) was applied to support the laterals and emitters. Ten driplines were arranged on the test platform and all of them were equipped with control valves at the front and back ends. The spacing between each lateral was 0.16 m. Each lateral pipe had 15 emitters, with a spacing of 0.3 m.

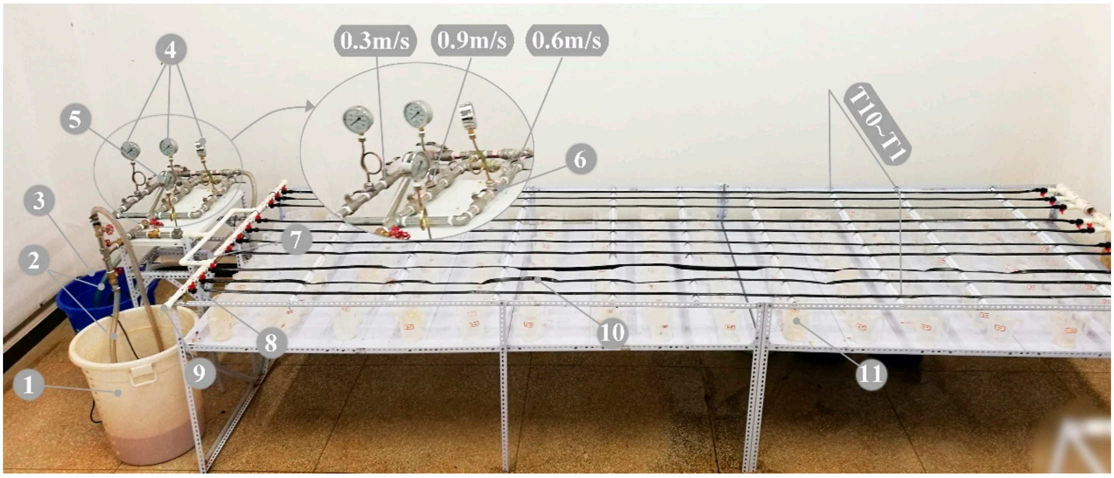


Figure 2. Experimental setup. 1, muddy water tank; 2, submersible pump; 3, clean water tank; 4, manometer I; 5, manometer II; 6, pressure adjustment valve; 7, polyvinyl chloride (PVC) pipe; 8, control valve; 9, PVC choke plug; 10, lateral; 11, measuring cup.

2.3. Measurement of Particle Size Distribution and Water Source

The distribution of particles size was analyzed by the Malvern laser particle size analyzer 2000 (Malvern Instruments Ltd., Malvern, UK). The measuring range of the particle analyzer was 0.02–2000 μm, and the particles were arranged in order of increasing size. When the accumulation volumes of sediment reached 10%, 50%, and 90%, the largest values of particle size were noted as D10, D50, and D90, respectively.

Tap water was used for lateral flushing in this study. Based on the maximum sediment concentration of irrigation water (0.8 g/L), the sand content in the muddy water was set at 2.5 g/L to accelerate the clogging process and reduce the experimental period. The test sediment was sandy loam soil obtained from Kunming, Yunnan Province of China, which was filtered using screens with 160 meshes after natural air drying. (In this study, 120 mesh screens were not selected for filtration to avoid insufficient test numbers caused by untimely clogging and the deposition of coarse particles.) Five sediment samples were randomly taken from the filtered sand after mixing well and the test sediment particle size distribution was presented based on their average values (see Table 1). The cumulative distribution and differential distribution of the tested sediments are shown in Figure 3.

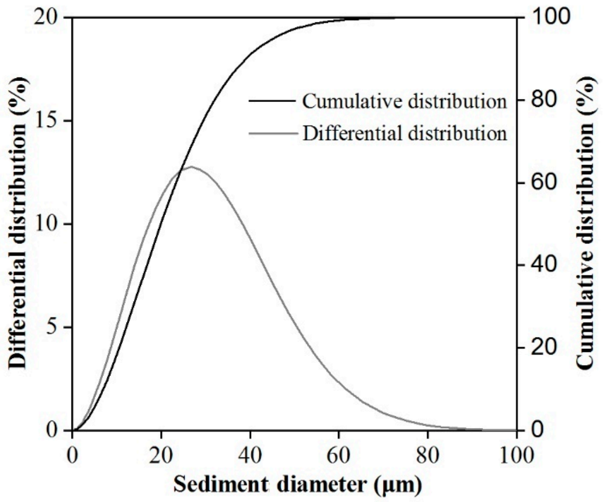


Figure 3. Differential distribution and cumulative distribution of sediments.

Table 1. Size distribution of sediment particles.

	D10	D20	D30	D40	D50	D60	D70	D80	D90	D100
Particle size	6.92	10.54	13.72	16.79	19.93	23.35	27.29	32.18	39.51	97.45
Standard deviation	0.34	0.45	0.55	0.63	0.72	0.82	1.00	1.27	1.65	1.33

2.4. Test Procedures

An experimental setup was conducted in a laboratory at Kunming University of Science and Technology, Kunming, Yunnan Province of China. In order to prevent the emitter flow rate and anti-clogging performance from being influenced by temperature variation, the experiments in this study were conducted between 13:00 and 16:00 CST, from 19 April to 7 September in 2017. Repeat experiments were carried out in three periods due to the limited width of the platform. The first repeated test was conducted between 19 April and 2 June, the second between 5 June and 19 July, and the third between 25 July and 7 September. The average temperature of the environment for the three test periods was 21.39 °C, 22.27 °C, and 22.08 °C, respectively.

2.4.1. Muddy Water Irrigation

The test conditions were as follows: normal irrigating pressure, 0.1 MPa; duration of irrigation event of each test, 20 min; initial volume of muddy water, 100 L; and total volume for each irrigation event, approximately 68.5 L. The muddy water was well stirred manually to avoid sedimentation. The emitter's discharge was measured every day using a marked 1000-mL measuring cup which was placed exactly beneath all the emitters. After each irrigation event, the weight of each measuring cup containing emitted muddy water was measured by a digital balance. The resolution of the digital balance was 0.01-g.

The emitter discharge was recorded as volume per unit time (L/h). For the emitter discharge less than 75% of the nominal rated flow, it was deemed to be clogged. The tested muddy water was replaced with new muddy water every day.

2.4.2. Sampling and Testing

The irrigation test was conducted with 45 events and 10 driplines, and the average discharge of all emitters in each lateral was taken into consideration. Therefore, 10 samples of each irrigation were measured three times. In all the tests, a total of 1350 (i.e., 45 × 10 × 3 = 1350) muddy water samples were evaluated. The distribution of particle size was measured with all emitters in each dripline. Ten samples were assigned to each irrigation event, and the process was repeated three times. A total of 1350 samples were measured.

2.4.3. Clean Water Flushing

The present study evaluated the effect of two factors: (1) the flushing frequency, either daily (F_1), once per three days ($F_{1/3}$), or once per five days ($F_{1/5}$); and (2) the flushing velocity, at either 0.3 m/s ($V_{0.3}$), 0.6 m/s ($V_{0.6}$), or 0.9 m/s ($V_{0.9}$). Table 2 shows 10 treatments consisting of a control non-flushed treatment (T10) and a combination of targeted flushing velocities and flushing frequencies (T1–T9). There was only one dripline being flushed in every experiment, and each flushing event lasted for 5 min.

Table 2. Flushing velocity and flushing frequency treatment.

Treatment No.	Flushing Velocity (V)	Flushing Frequency (F)	Average Irrigation Events Before Emitter Clogging (d)
T1	$V_{0.3}$	F_1	32.67
T2	$V_{0.3}$	$F_{1/3}$	30.67
T3	$V_{0.3}$	$F_{1/5}$	27.33
T4	$V_{0.6}$	F_1	39.67
T5	$V_{0.6}$	$F_{1/3}$	33.67
T6	$V_{0.6}$	$F_{1/5}$	29.00
T7	$V_{0.9}$	F_1	41.33
T8	$V_{0.9}$	$F_{1/3}$	36.67
T9	$V_{0.9}$	$F_{1/5}$	30.67
T10	No flushing		23.33

2.5. Statistics

The data were analyzed using SPSS software for Windows, version 22.0 (IBM Corp., Chicago, IL, USA). Based on main effects analysis of variance (ANOVA), the significance of the differences between treatments for different response variables was evaluated. Furthermore, the results were categorized as "descriptive statistics" (such as mean) and Levene's test of equality of error variances. In addition, multiple comparisons were carried out based on Fisher's least significant difference tests because significant differences ($p < 0.05$) were indicated by ANOVA.

3. Results

3.1. Variations in Emitter Discharge

Figure 4 illustrates the value changes of the emitter discharge versus irrigating events. The level of straight line was 75% of the initial discharge, which was used as the criterion for emitter inefficiency or severe emitter clogging. Ten discharges of the emitters treated under diversified conditions showed a descendant trend with increasing irrigation events, suggesting that clogging with different degrees was seen in emitters until their service life ended. In the figure, the bold black line shows changes of the emitter discharge in T10, the control experiment. The emitter discharge in treatment T10 reached 75% of the rated discharge first, and its average discharge at the end of the test was the minimum without any flushing treatments made after irrigation. According to the irrigating events (Table 2), T10 provided only 23.33 irrigation events before emitters were severely plugged. However, for the remaining nine flushing treatments, the average normal irrigating event was 33.52, which indicated that the emitter's average service life in the flushed driplines after irrigation increased by 30.40% in comparison with those in the non-flushed T10. In the nine flushing treatments, treatment T7 had the longest irrigation event 41.33 and the universally largest average discharge; treatment T3 had the shortest irrigation event 27.33 and the universally lowest average discharge after 28 irrigation events. The service life of treatments T7 and T3 increased by 43.55% and 14.64%, respectively, compared with the non-flushing group T10. Additionally, treatments T7 and T3 were flushed at the frequency of F_1 and $F_{1/5}$ and at the velocity of $V_{0.9}$ and $V_{0.3}$, respectively, demonstrating that the emitters had a longer service life under high flushing velocities and high flushing frequencies.

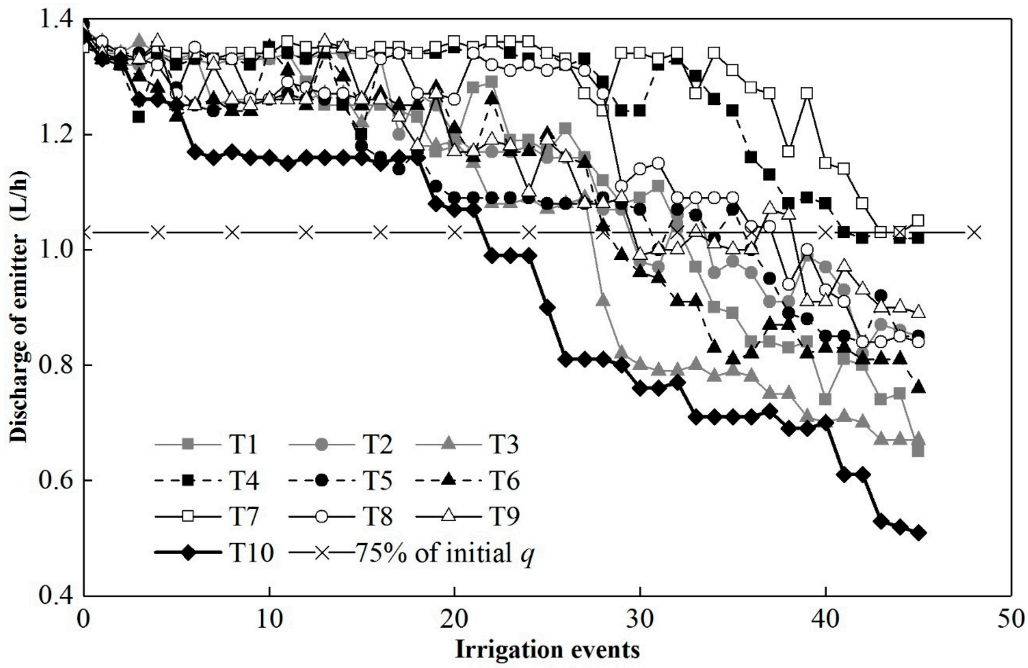


Figure 4. Average change in the emitter discharge versus irrigating events.

3.2. Variance Analysis of the Two Flushing Factors on the Service Life of Emitters

Flushing velocity and flushing frequency have significant effects on the service life of emitters, and the interactions were negligible (see Table 3). Figure 5a shows that the service life of emitters increased with the increase in the flushing velocity. The average service life of emitters was 22.80%, 31.60%, and 35.59% higher under $V_{0.3}$, $V_{0.6}$, and $V_{0.9}$ conditions, respectively, compared with the non-flushing conditions. Moreover, the service life of emitters under $V_{0.6}$ and $V_{0.9}$ conditions was similar, which meant that the flushing velocities in excess of 0.6 m/s would only help improve the service life to an insubstantial degree. Therefore, 0.6 m/s proved to be the optimal flushing velocity.

Table 3. Variance analysis of the effects of flushing velocity and flushing frequency on the service life of emitters.

Factors	*F* Value
Flushing velocity	21.94 **
Flushing frequency	46.82 **
Flushing velocity × Flushing frequency	2.03

* $p < 0.05$; ** $p < 0.01$.

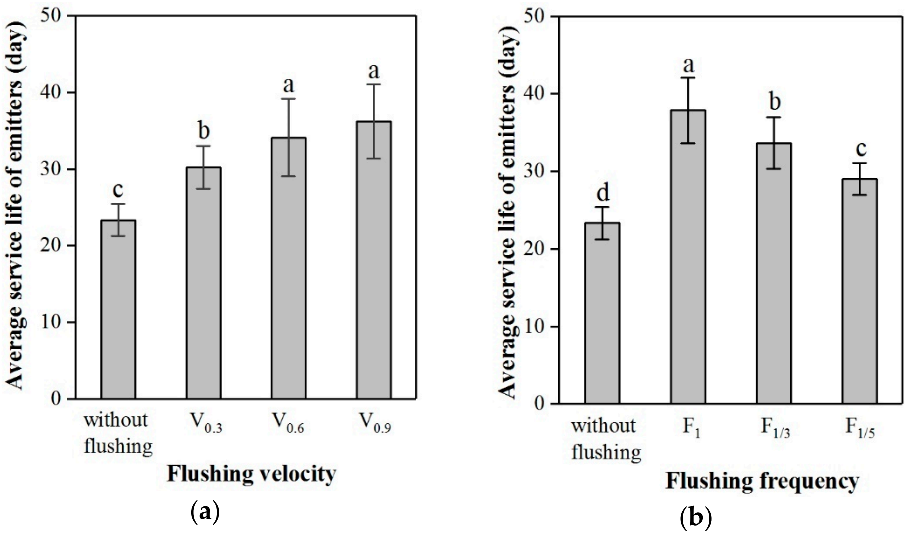


Figure 5. Average service life and standard errors of emitters at different flushing (**a**) velocities and (**b**) frequencies.

On the contrary, the service life of emitters was significantly reduced as the flushing frequency decreased (Figure 3b). The average service life of emitters was 38.43%, 30.71%, and 19.55% higher under F_1, $F_{1/3}$, and $F_{1/5}$ conditions, respectively, compared with the non-flushing treatment, indicating that a decrease in the flushing frequency effectively extended the service life of emitters.

3.3. Particle Size of Discharged Sediments

Table 4 shows that the effect of flushing velocity on D90 was significant, indicating that coarse particles passing through the labyrinth channel were affected by the flushing velocity, whereas fine particles were not. The flushing frequency had no effect on the particle size of discharged sediments. Figure 6 shows that D10, D50, and D90 mean values under non-flushing measures were 3.00, 7.16, and 12.65 μm, respectively, which were significantly higher than the different processing levels of flushing velocity and flushing frequency. This can be attributed to the fact that residual sediments in the lateral were discharged by flushing, resulting in a reduced concentration of sediments at the inlet of the labyrinth channel. Figures 7 and 8 show large amounts of residual sediments in the non-flushing lateral. The sediments mixed together, and more coarse particles flew into the labyrinth channel with the turbulence of the flow. Therefore, flushing effectively reduced the concentration of residual sediments in the lateral and decreased the probability of large particles entering into the labyrinth channel. Meanwhile, Figure 6b shows that the degree of D90 increased slightly with the decrease in the flushing frequency for the same reason.

Table 4. Variance analysis of the effects of flushing velocity and flushing frequency on the particle size of discharged sediments.

Factors	*F* Value		
	D10	**D50**	**D90**
Flushing velocity	2.15	3.38	4.18 *
Flushing frequency	0.66	1.20	3.41
Flushing velocity × Flushing frequency	0.14	0.39	0.91

* $p < 0.05$; ** $p < 0.01$.

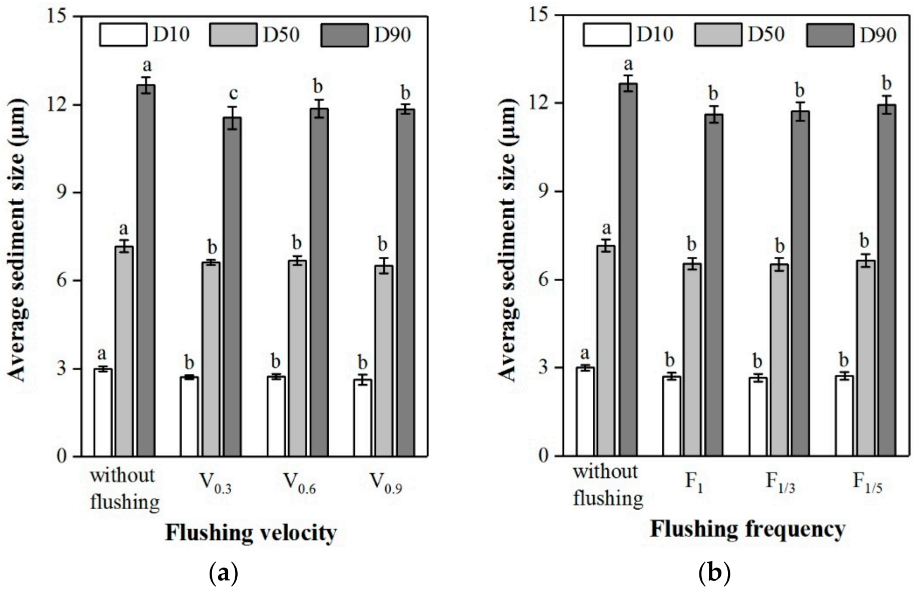


Figure 6. Average and standard errors of D10, D50, and D90 at different flushing (**a**) velocities and (**b**) frequencies.

3.4. Residual Sediments in Drip Tape and Emitters

Emitters and pipe sampled from the driplines were cut open to provide visual proof of clogging when experiments were finished (Figures 7 and 8). A few sediments were observed on the inner walls of the lateral with flushing treatment, whereas substantial sediment accumulations were observed in the lateral without flushing (Figure 5). Hence, flushing can effectively prevent particles from accumulating in the drip tape and emitters. Figure 8 shows that the sediment particles were seldom deposited in the labyrinth channel and the outlet of emitters due to flow turbulence with flushing, whereas clogging particles were found along the labyrinth channel of emitters without flushing, especially at the outlet. Additionally, other impurities such as plant root debris, which were not or seldom observed in the labyrinth channel of emitters with flushing treatment, were widely distributed in the labyrinth channel of emitters without flushing. In summary, flushing could effectively remove residual sediments and other impurities in the labyrinth channel, thus enhancing the anti-clogging performance of emitters.

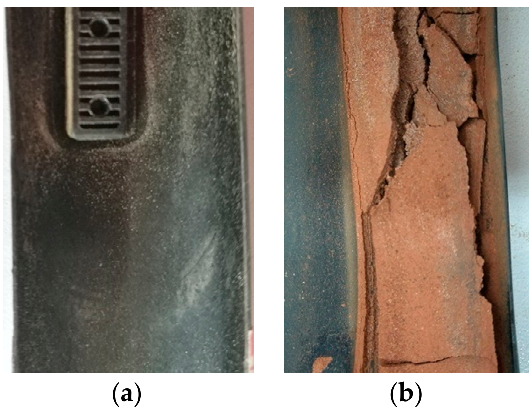


Figure 7. Residual sediments in the drip tape after tests. (**a**) Drip tape with flushing treatment; (**b**) drip tape without flushing treatment.

(**a**) (**b**)

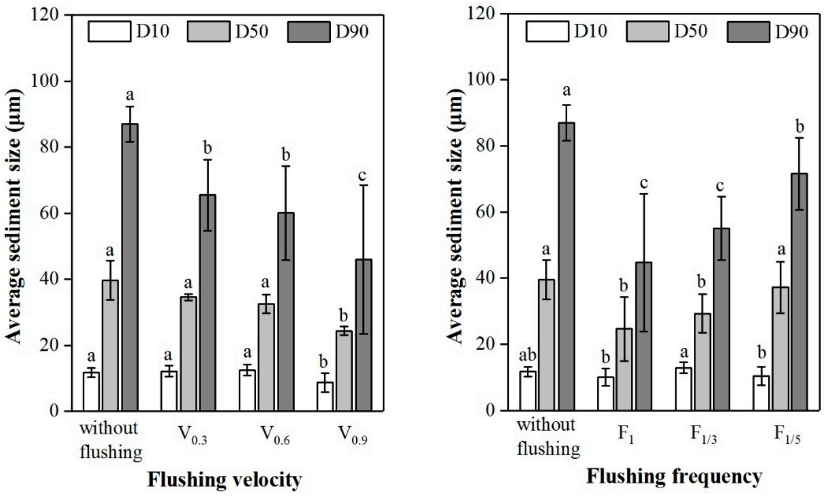
Figure 8. Residual sediments in the labyrinth channel of emitters (yellow parts indicate that the clogging substances are other impurities, not sediments). (**a**) Emitters with flushing treatment; (**b**) emitters without flushing treatment.

Table 5 shows the variance analysis of clogging substances in emitters. The flushing frequency and flushing velocity had significant effects on D10, D50, and D90. Figure 9 shows that D50 and D90 were the highest under non-flushing conditions, being 30% and 52% higher than the averages under the corresponding flushing conditions, respectively, indicating that flushing prevented large particles from entering into the labyrinth channel. The figure also shows that D50 and D90 decreased as the flushing velocity increased. For instance, D10, D50, and D90 under $V_{0.9}$ conditions were the minimum, being, respectively, 25.76%, 38.55%, and 47.14% lower than those under non-flushing conditions. In summary, a higher flushing velocity contributed to the discharge of coarse particles in emitters, thereby lowering risks of emitter clogging.

Table 5. Variance analysis of the effects of flushing velocity and frequency on the particle size of residual sediments in emitters.

Factors	*F* Value		
	D10	D50	D90
Flushing velocity	18.07 **	7.48 **	10.85 **
Flushing frequency	10.06 **	10.36 **	19.58 **
Flushing velocity × Flushing frequency	2.81	2.47	2.67

* $p < 0.05$; ** $p < 0.01$.



(**a**) (**b**)

Figure 9. Average and standard error of D10, D50, and D90 at different flushing (**a**) velocities and (**b**) frequencies.

Figure 9 further shows that D50 and D90 increased as the flushing frequency decreased and was maximized under non-flushing conditions. D90 under F_1, $F_{1/3}$, and $F_{1/5}$ conditions was 48.50%, 36.63%, and 17.66%, respectively, significantly lower than that under non-flushing conditions. D50 under F_1 and $F_{1/3}$ was 37.60% and 25.85%, respectively, significantly lower than that under non-flushing conditions. However, D10 differed slightly between the F_1, $F_{1/3}$, and $F_{1/5}$ conditions. A low flushing frequency caused the accumulation of sediments in the lateral and increased the probability of large particles being trapped in the labyrinth channel, resulting in increased particle sizes of residual sediments in the channel. It also favored the agglomeration of sediments, resulting in a higher degree of D50 and D90. Combining these two effects, the flushing frequency had a significant effect on the size distributions of residual sediments in the labyrinth channel.

4. Discussion

4.1. Influence of Flushing Treatment on Emitter Clogging

For drip irrigation systems, appropriate flushing can effectively prevent emitter clogging by hindering the agglomeration of sediment particles or their adhesion to organic residuals to generate large particles [23,24]. This study demonstrated that lateral flushing using clean water after the irrigation of muddy water could enhance the service life of emitters by 14.64–43.55% compared with non-flushing cases, and both the flushing velocity and flushing frequency significantly affected the service life of emitters. However, Puig-Bargués et al. [18] reported that the flushing frequency and flushing velocity had little effect on the resulting emitter discharges in subsurface drip irrigation systems measured at the end of the study. The results were different from the findings of the present study mainly due to different irrigation systems and flushing operations.

Recent studies found that the service life of emitters increased with the increase in the flushing velocity. For instance, the service life of emitters flushed at the velocities of 0.6 and 0.9 m/s was extended by more than 30% compared with that without flushing. This paper held that the flushing velocity of 0.6 m/s would appear to be adequate. In a laboratory study simulating a dripline with a transparent PVC pipe, Puig-Bargués and Lamm [25] suggested that the minimum flushing velocity of 0.3 m/s appeared sufficient for most micro-irrigation systems working under typical conditions. This was not consistent with the findings in this paper, which could be attributed to the fact that the researchers did not fully consider the complexities of the flow regime that might occur in the emitter. Zhang et al. [26] compared the influence of constant pressure and pulse pressure on the anti-clogging performance of the labyrinth emitter. According to their findings, the pulse pressure could alleviate clogging and reduce discharge of the emitter. Some studies [27,28] demonstrated that the emitter's anti-clogging performance could be enhanced by increasing the flushing pressure. This was consistent with the conclusion of this study because the pressure of flushing was proportional to the velocity of flushing.

In this study, the service life of emitters degraded significantly in the order of $F_1 > F_{1/3} > F_{1/5} >$ without flushing. Li et al. [21] conducted an in situ surface drip irrigation experiment under three conditions of dripline flushing frequency, in which the recycled water from a sewage disposal plant was used. They reported that lateral flushing could significantly relieve the emitter clogging of the irrigation systems using reclaimed water. Elberry et al. [23] reported that clogging at a high flushing frequency was significantly lower than that at a low flushing frequency. The aforementioned study results are consistent with the findings of this study. Nevertheless, Feng et al. [29] found that emitter clogging was not prevented with five different frequencies of flushing in the drip irrigation experiment using salty groundwater, which is primarily affected by flushing operations and water quality.

4.2. Influence of Flushing Treatment on Particle Size Distributions

Flushing can effectively enhance the anti-clogging performance of emitters by removing residual sediments from the dripline and maintaining the cleanliness and the passability of the labyrinth channel [29,30]. The results of this study indicated that the passability of large sediment particles in the labyrinth channel was the dominant factor for emitter clogging. In this study, the corresponding pressure in emitters was 0.004, 0.008, and 0.016 MPa, which was much less than 0.1 MPa, the normal irrigation pressure under the flushing velocity of 0.3, 0.6, and 0.9 m/s, respectively. Nevertheless, this study demonstrated that these relatively low pressures still had a significant effect on the particle size of residual sediments in the labyrinth channel. Kou et al. [31] reported that a disordered system of granular materials, such as powders, sand, and foams, formed stable structures when unperturbed, but that they "relax" in the presence of external influences such as shear or tapping, becoming fluid in nature. Similarly, the slightest perturbation of a particle system due to flushing destabilized some of the particles trapped in the labyrinth channel of emitters, increasing the flowability of particles in the channel. Hence, the passability of the labyrinth channel was enhanced, thus extending the service life of emitters. In this study, D90 of discharged sediments was significantly affected by the flushing velocity. Specifically, D90 under $V_{0.9}$ was significantly larger than that under $V_{0.3}$ and $V_{0.6}$ and without flushing, indicating that the perturbation of the particles increased with the increase in the flushing velocity and resulted in the increased trafficability of coarse particles.

A certain concentration of particles is indispensable for the follow-up collision and flocculation of particles. As particle concentration in the influent water increased, the local concentration distribution of particles in the labyrinth channel was improved [32–34]. In this study, the particle size of discharged sediments increased with the increase in the flushing frequency and reached its maximum under non-flushing conditions. As the flushing frequency decreased, fine particles were continuously discharged from the emitters, resulting in an increase in the relative contents of coarse particles and concentration of sediments, thereby improving the probability of collision, sedimentation, and accumulation of large sediment particles. This was why D50 and D90 of residual sediments in emitters increased with the increase in the frequency of flushing.

4.3. Influence of Particle Size on Emitter Clogging

The clogging mechanism in the emitter is dependent on the particle size of sediments. Coarse particles readily underwent collision and deposition in the vortices of the water flow due to bigger sizes and the larger drag force of the particles. Therefore, the particles could not escape from the vortices. On the other hand, the major forces causing the fine particles to clog came from their surface tension and adhesion to surrounding substances. In this study, D10 and D50 of discharged sediments were not affected by flushing velocity or flushing frequency, indicating that fine particles had better flow characteristics due to their lower drag force in the flow. In other words, this study demonstrated that coarse particles tended to be trapped in the labyrinth channel, which was consistent with the findings of previous studies [35–38].

Wu et al. [39] pointed out that it was difficult to cause clogging when the particle size was less than 20 mm. Particles <20 mm took up 50% of the muddy water (see Table 1), whereas D90 of discharged sediments was significantly lower than 20 μm (Table 6). Moreover, D100 of discharged sediments was only 27.18 μm. This indicated that particles larger than 20 μm tended to stay in the labyrinth channel and that particles smaller than 20 μm could easily flow out with the water. Table 6 shows that D50 of residual sediments in emitters was 24.38–39.67 μm, which was 22–99% higher than that in the initial water. In addition, D90 of residual sediments in emitters was 44.74–86.89 μm, which was 13–120% higher than that in the initial irrigation water resource.

Generally, the agglomeration and flocculation of fine particles occurred during the flow, and the upper-limit particle size was 10 μm [40]. Table 6 shows that the percentage of particle sizes below 10 μm was 10% in the residual sediments in the labyrinth channel but 90% in the discharged sediments. Hence, the emitter plugging in this study was caused mainly by large residual sediment particles in the emitter's labyrinth channel, instead of the agglomeration and flocculation of small sediment particles. This could be attributed to high flushing velocity and high flushing frequency.

Table 6. Average particle size of residual sediments in emitters and discharged sediments (µm).

		D10	D50	D90	D100
Discharged sediments	With flushing	2.68 ± 0.07	6.56 ± 0.14	11.73 ± 0.25	25.30 ± 0.50
	Without flushing	2.98 ± 0.29	7.17 ± 0.42	12.70 ± 0.74	27.18 ± 3.05
Residual sediments in emitters	With flushing	11.14 ± 2.30	30.49 ± 8.14	57.12 ± 14.68	69.63 ± 9.67
	Without flushing	11.74 ± 1.41	39.67 ± 5.92	86.88 ± 5.32	89.68 ± 6.71

5. Conclusions

The nine flushing measures led to an enhancement of 30.40% in the service life of emitters on average, and both flushing velocity and flushing frequency had significant effects on the service life of emitters. Although the life of emitters flushed at 0.9 m/s was longer than that of emitters flushed at 0.6 m/s, the numerical differences were small (<4%). Therefore, the flushing velocities setting at around 0.6 m/s appeared to be sufficient. Increasing the flushing frequency would be an economical way to achieve the optimal flushing effect without providing a higher flushing velocity, which might increase the system cost. Moreover, the inner walls of the lateral were clean in the presence of flushing and only local clogging was observed in the labyrinth channel. Severe sedimentation was observed in the lateral in the absence of flushing, and the clogging by sediments was observed along the labyrinth channel. Furthermore, flushing decreased the accumulation of sediments in the lateral, which prevented large sediment particles from entering into the labyrinth channel and lowered the probability for small sediment particles to agglomerate and flocculate into large particles, thus reducing the risks of emitter clogging.

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