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Performance and potential on TSS removal of grassed swales in simulated rainfall events

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ABSTRACT

Grassed swales are a low-cost storm water, low-impact development facility. The performance on total suspended solids (TSS) concentration removal, runoff volume reduction, and TSS load removal of grassed swales is evaluated from hydraulic load, initial concentration, and influent pattern. The results indicate that the ratios of TSS concentration removal range from 2.8% to 42.3%. Hydraulic load and initial concentration are the key factors for TSS concentration removal by grassed swales. Runoff reduction rates of grassed swales range from 5.11% to 13.46%, which is influenced significantly by contact area and hydraulic residence time. The peripheral overland influent swales present better performance on runoff volume reduction than others. The ratios of TSS load removal by grassed swales range from 8.36% to 46.77%, which is contributed by the combined action of vegetation interception, particle sedimentation, and infiltration. The influent pattern of grassed swales is little influence to the efficiency of TSS load removal.

Keywords: Grassed swales; Total suspended solids (TSS); Removal efficiency; Hydraulic load; Initial concentration; Influent pattern

1. Introduction

Under the rapid urbanization, natural vegetation has been converted into impervious surface in many cities worldwide, which brings about a reduction of natural infiltration and groundwater recharge from storm water runoff [1–3]. More and more untreated storm water runoff is discharged into surface water bodies. Although the treatment of conventional point pollution (such as domestic sewage and industrial wastewater) has been strengthened constantly, the quality of surface water environment does not have significant improvement. Gradually, storm water runoff has been identified as a major cause of urban water contaminations [4]. There are a variety of particles in storm water runoff, which may be the main carriers of nutrients and metals. They may cause serious damage to the environment. In an effort to reduce the influence of nonpoint source pollution, low-impact development (LID) practices are gradually developed to cope with water quality problems in many countries.

Grassed swales, as one of the technical measures of LID practices, are used for storm water collection, transportation, and treatment. Swales are shallow, flat bottomed, and vegetated open channels to receive runoff flow with different influent patterns. And it is acknowledged that grassed swales have a significant effect on the water quality enhancement by the process of infiltration, sedimentation, and filtration [6]. Previous studies proposed that the major pollutant removal mechanisms in grassed swales were suspended solids sedimentation [7,8]. However, total suspended solid (TSS) removal rate of the swales exists obvious variation in different literatures. The efficiency of TSS removal in the storm water runoff by the swales is influenced by multiple factors.

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There were experiments that analyzed the exponential decay of TSS concentration in grassed swales and found that hydraulic residence time, which was influenced by the longitudinal slope and length of grassed swales, was the decisive factor of TSS removal performance. When decreasing the longitudinal slope and increasing the length of swale, the reaction will be prolonged [9]. During a study of grassed swale in laboratory, which constructed two 5 m-long laboratory swales with thin vegetation and fully developed turf, it was found that grass height and grass spacing were important parameters for the TSS removal. But any significant relationship between TSS removal and swales length was not shown [5]. Two common roadside swales were conducted at MD Route 32, Maryland, USA. Forty-five storm events over 4.5 years were studied and found that TSS was reduced from 41.2% to 2.6% and 1.2% in the swales with and without filter strips, and from 55.7% to 19.2% and 18.0% in the filter strips-check dam swales and swales without filter strips and check dam [10]. It is far below some previous studies, which exhibited TSS removal efficiency of 65%–98% [11], 85%–87% [12], 94% [13], 79%–98% [14], and 48% [15], respectively. Moreover, many studies also pointed out that TSS removal of grassed swales was a principal physical process, which was connected with settling velocity. It was 73%–94% TSS concentration removal and 57%–88% TSS load removal for a 65 m roadside swale as hydraulic loading ranging from 2 to 15 L/s [7]. Besides, to predict the TSS reduction of the swales more flexibility, some researchers created hydraulics and particle-setting model, rainfall runoff model, hydrological and hydraulic model, and so on [16–18].

Because there are differences in plain layout and connection mode of grassed swales and corresponding catchments for each engineering case existing of LID practices, common influent patterns of grassed swales can be broadly split in three basic types (Fig. 1): centralized source influent (CSI), peripheral multipoint influent (PMI), and peripheral overland influent (POI). Most studies of grassed swales focus on a specific influent pattern only.

The objectives of this study are mainly to discuss the performance and potential on TSS removal of grassed swales in different influent patterns. An artificial simulation apparatus of grassed swales is designed in the laboratory to evaluate the performance of TSS removal, which can simulate different experiment conditions, such as influent pattern, pollutant load, and hydraulic load. By monitoring influent and effluent concentrations and flow, removal efficiencies of TSS concentrations and loads in different influent patterns are evaluated quantitatively. Some reasonable proposals on influent pattern choice of grassed swales will be put forward to enhance TSS removal by grassed swales in urban storm water management.

2. Materials and methods

2.1. Experimental apparatus

The artificial simulation apparatus of grassed swales is manufactured by steel plate. It is a group of rectangular body without cover (Fig. 2). There are two evenly distributed vent pipes with a diameter of 25 mm at the bottom of the apparatus. The inflow is provided by an inlet tank (2 m^3 plastic tank) equipped with a submerged pump placed at the beginning of the swales. At the end of the swales, there is an outlet tank with the same specifications of inlet tank, in which there is a circulating pump used to pump back the water after the experiment. A flowmeter and a flow control valve are installed at the inlet pipe to adjust the influent flow of the swales during the experiments. There is a mixing pump at the bottom of inlet and outlet tanks, respectively, to prevent the sedimentation of suspended particles. And in consideration of influent and effluent flow monitoring, liquid level gauges are added at the inlet and outlet tanks.

The swale apparatus is 5.0 m long, 1.0 m wide, and 0.5 m high, mounted on a 1.2 m high support frame. The typical surface soil of North China is selected as the swales matrix, which is compacted in the steel box. The swales are designed to be a triangular cross-section with 3‰ longitudinal slope and 2.0 slope coefficient. As the popular grass type in North China, meadow grass is sowed in the topsoil of the swales. The sowing density of grass seeds is about 20 g/m^2.

This study selected 2, 4, and 8 m^3/h as influent hydraulic load and 200, 500, and 1,000 mg/L as influent concentration load. When the influent is run from the intake directly, the influent pattern could be seen as CSI. If the influent patterns of PMI and POI are simulated, the intake should be connected with other water distribution pipelines (Fig. 3).

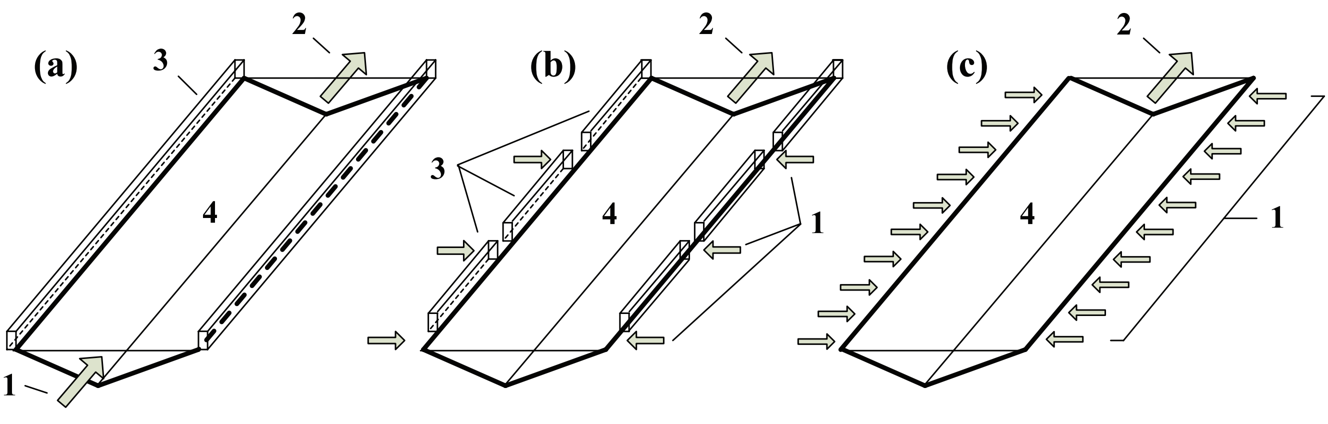

Fig. 1. Common influent patterns of grassed swales: (a) centralized source influent (CSI), (b) peripheral multipoint influent (PMI), and (c) peripheral overland influent (POI) (1, influent; 2, efluent; 3, road shoulders; and 4, grassed swales).

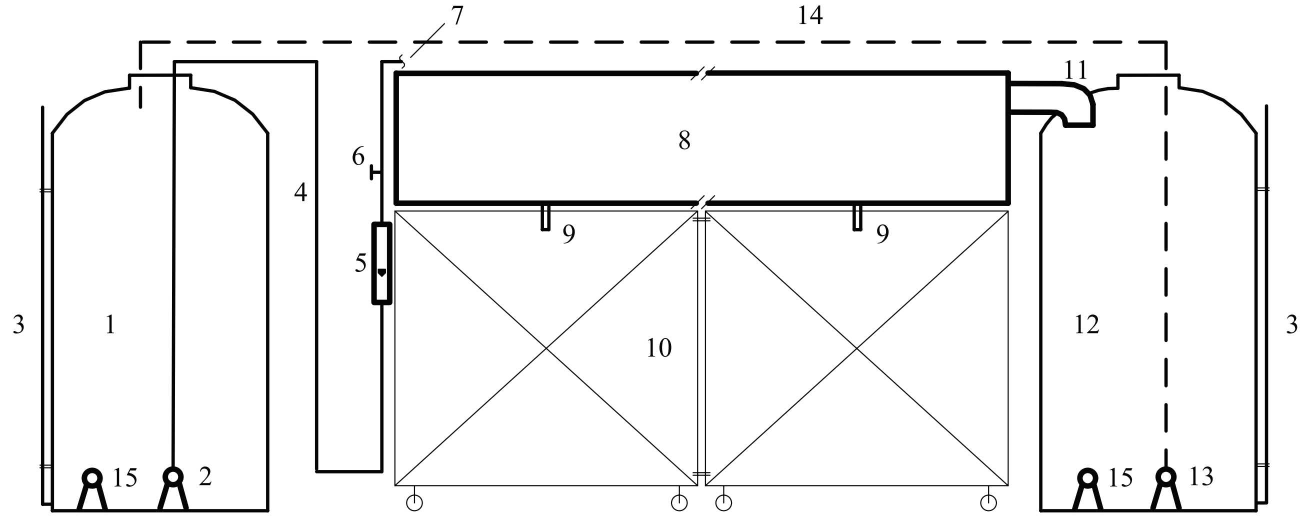

Fig. 2. Artificial simulation apparatus of grassed swales (1, inlet tank; 2, inlet pump; 3, liquid level meter; 4, distribution pipe line; 5, flowmeter; 6, flow control valve; 7, intake [or connect with distribution pipeline]; 8, grassed swale device; 9, vent pipe; 10, device support; 11, outlet pipe; 12, outlet tank; 13, circulating pump; 14, circulating pipe line; and 15, mixing pump).

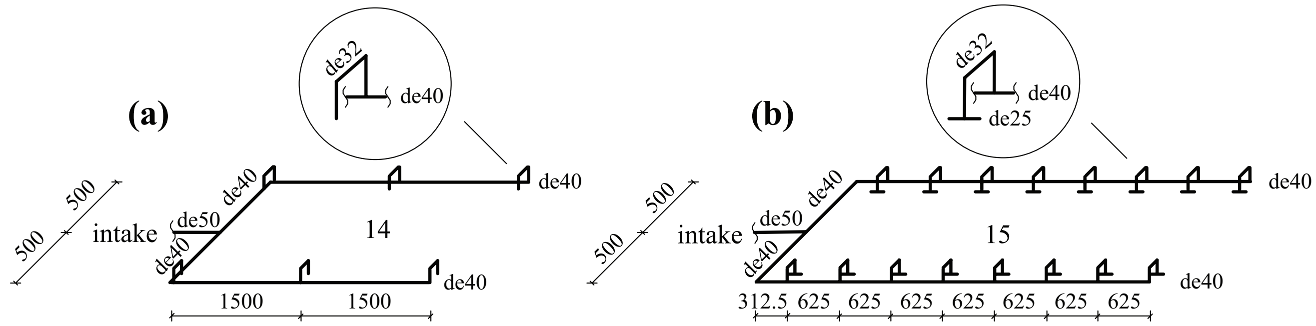

Fig. 3. Water distribution pipeline connected with the intake for (a) PMI and (b) POI.

2.2. Experimental design

The experiments are conducted under three influent patterns, three hydraulic loads, and three initial concentrations. Suspended particles and water are mixed in the inlet tank to realize required TSS concentration load 1.5–2 h before the experiments started [5]. Different hydraulic loads are achieved by adjusting the flow control valve according to the flowmeter. The 2 m^3/h hydraulic load is equivalent to the runoff from a catchments area of single-lane road in the rainfall of 2-years recurrence period, 4 m^3/h is equivalent to double-lane road in 3-years recurrence period, and 8 m^3/h is four-lane road and 3-years recurrence period. The types of PMI and POI are achieved by the water pipelines distributed on both sides of swales. The significant difference between PMI and POI is the outlet spacing, which is the important factor in influent patterns simulation.

The water level of inlet and outlet is recorded continuously by the liquid level meter per minute during experiment studies; thereby, the inlet and outlet flow rate and water loss due to infiltration is calculated. Mean TSS concentrations are monitored in the inlet tank before experiment and at the outlet tank after experiment according to the standard method 2540-D [19]. At the end of experiment, the water in the outlet tank is pumped back to the inlet tank by circulating pump. The total experimental period is 15–30 min, and the adjacent experiment interval is 5 d apart to ensure that the initial moisture content of the surface soil is similar. Experiments are performed in swales within 7 d of mowing, and the grass height is controlled at 10–15 cm.

2.3. Hydrology calculation and data evaluation

The efficiencies of TSS concentration removal of grassed swales are calculated by the TSS concentration monitored at the inlet tank before experiment and the outlet tank after experiment.

$$\eta_c = \frac{C_0 - C}{C_0} \times 100\% \tag{1}$$

where η_c is the efficiency of TSS concentration removal of grassed swales (%), C_0 is initial concentration of TSS at the inlet tank before experiment (mg/L), and C is TSS concentration treated by grassed swales at the outlet tank after experiment (mg/L).

Runoff reduction volume and runoff reduction rate are used to express the characters of runoff hydrology control by grassed swales, and the values could be determined by Eqs. (2) and (3).

$$\Delta V = V_0 - V = A\left(\Delta h_{\text{in}} - \Delta h_{\text{out}}\right) \tag{2}$$

$$\eta_V = \frac{V_0 - V}{V_0} \times 100\% = \frac{\Delta h_{in} - \Delta h_{\text{out}}}{\Delta h_{\text{in}}} \times 100\% \tag{3}$$

where ΔV is the runoff reduction volume (m^3), η_V is runoff reduction rate (%), V_0 is the outflow volume from the inlet tank (m^3), V is the inflow volume into the outlet tank (m^3), A is the bottom area of the swales (m^2), Δh_{in} is the liquid level variation in the inlet tank (m), and Δh_{out} is the liquid level variation in the outlet tank (m).

The ratio of TSS load removal is an indicator used to describe the efficiency of TSS load control by grassed swales, which is calculated as follows:

$$\eta_L = \frac{L_{\text{in}} - L_{\text{out}}}{L_{in}} \times 100\% = \frac{V_0 C_o - VC}{V_0 C_o} \times 100\% = \frac{\Delta h_{\text{in}} C_0 - \Delta h_{\text{out}} C}{\Delta h_{\text{in}} C_0} \times 100\% \tag{4}$$

where η_L is the ratio of TSS load removal (%), L_{in} is the influent TSS load of grassed swales (kg), and L_{out} is the effluent TSS load of grassed swales (kg).

3. Results and discussion

3.1. TSS concentration removal

Fig. 4 shows the mean removal efficiencies of TSS concentration under the different conditions by the artificial simulation experiment, which is calculated by Eq. (1). The efficiencies observed in the experiment are of range 2.8%–42.3%, which is influenced significantly by the hydraulic load and initial concentration. Under the same hydraulic load and initial concentration, the removal efficiencies of TSS concentration with different influent patterns are following this order: CSI > PMI > POI. It is because that when grassed swales adopt the influent pattern of CSI, storm water runs across the whole swales, the hydraulic residence time of which is longer than other influent patterns. Hydraulic residence time is a key factor to influence the TSS removal of grassed swales [9]. The extension of hydraulic residence time will enhance the efficiencies of TSS removal. However, because the swales length is only 5 m in this study, the efficiencies among the three influent patterns have no particularly change. With the lengthening of the swale, the change might be more obvious [20,21].

From Fig. 4, an interesting phenomenon can be found that grassed swales of three influent patterns have the same variation tendencies on TSS removal efficiencies with different hydraulic load and initial concentration. For example, when the CSI swales are taken, the influences of hydraulic load and initial concentration on TSS removal of grassed swales are analyzed.

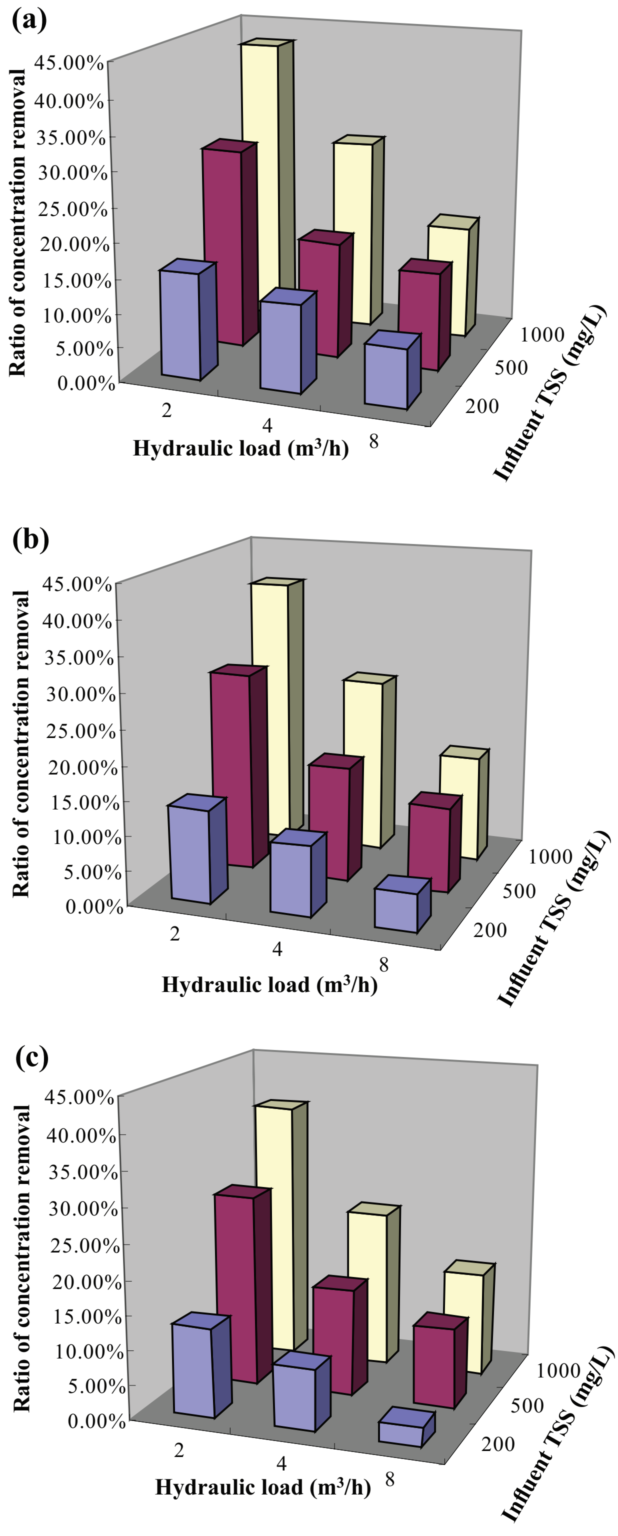

Fig. 4. TSS concentration removal efficiency under different conditions: (a) the CSI swales, (b) the PMI swales, and (c) the POI swales.

For the CSI swales (Fig. 4(a)), with initial concentration of TSS ranging from 200 to 1,000 mg/L, TSS removal efficiencies ranged from 15.41% to 42.30% with 2 m^3/h hydraulic load, from 12.78% to 28.31% with 4 m^3/h, and from 8.39% to 16.79% with 8 m^3/h. With the increasing hydraulic load and the declining initial concentration, TSS removal efficiencies of grassed swales decrease continuously. The higher the initial concentration of grassed swales, the more obvious the decreasing trend of TSS removal efficiencies with the increasing hydraulic load. That may be because low hydraulic load would decrease the velocity of the storm water runoff in the grassed swales, which can also prevent soil erosion to a certain extent. It is helpful to suspended particles removal in the runoff by vegetation interception and particle sedimentation. Besides, when storm water run across the swales, it is unavoidable that the swale bed is scoured by the runoff. Parts of the suspended particles depositing on the swale surface are captured into the runoff. Some previous research proposed that swales had background TSS concentration values of 0–40 mg/L [8,20,21]. With low initial concentration, the efficiency of grassed swales for TSS removal is disturbed by the background TSS concentration value, so the efficiency will be presented well under high initial concentration. Thus, high removal efficiencies are positively correlated with low hydraulic load and high initial concentration.

3.2. Runoff volume reduction

Fig. 5 shows the mean runoff reduction volume and runoff reduction rate of grassed swales under different influent patterns and hydraulic loads, which presents a similar trend for runoff control. Using Eqs. (2) and (3), runoff reduction rates range from 5.11% to 13.46% at the condition of CSI swales with 8 m^3/h hydraulic load and POI swales with 2 m^3/h hydraulic load.

Compared with the three different influent patterns, the POI swales have a better performance, whether from the runoff volume reduction or from the runoff reduction rate. That may mainly be related to the contact area between the runoff and swales surface, which brings more opportunity for infiltration. For the CSI swales, the runoff across the swales only contacts with the surface soil at the bottom of the swales. Besides the bottom, partial sides of the swales also contact with the runoff for the PMI swales. In the POI swales, the contact area includes the bottom and most sides of the swales. So, the POI swales present better performance on runoff volume reduction than others. Meanwhile, the wetted perimeter of the swale transects will increase with the increase of hydraulic load, which can reduce the difference on the contact area among the swales using different influent patterns. The efficiencies of runoff volume control by grassed swales are also closer.

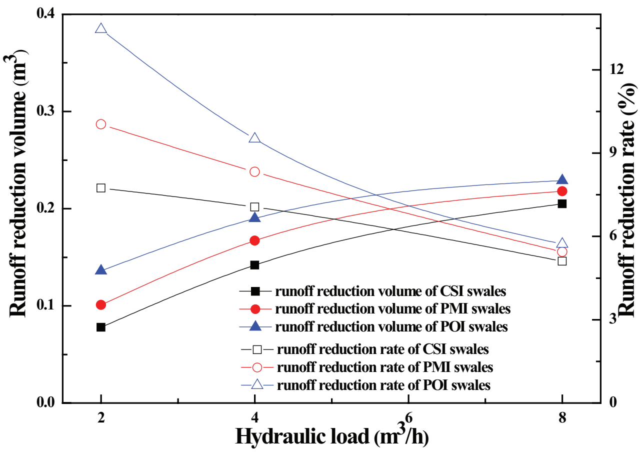

Fig. 5. Runoff volume reduction and runoff reduction rate of grassed swales under different influent patterns and hydraulic load.

However, with the increasing hydraulic load, the trends on the runoff volume reduction are increased slowly and the runoff reduction rates are even decreased. It might result from the hydraulic residence time of the swales [9]. In this study, the total runoff volume is 2 m^3 at each experiment. When the hydraulic load is 2, 4, and 8 m^3/h, the hydraulic residence time corresponding is about 1, 0.5, and 0.25 h, respectively. Under the combination of the hydraulic residence time and the contact area, the transformation of runoff volume reduction and runoff reduction rate of grassed swales are presented same as shown in Fig. 5.

3.3. TSS load removal

According to the data of grassed swales for the storm water runoff control above, the ratio of TSS load removal could be calculated by Eq. (4). The results are shown in Fig. 6.

The mean ratios of TSS load removal by grassed swales range from 8.36% to 46.77%, which appears to be a slight increase by infiltration contrasting with 2.80%–42.30% of TSS concentration removal. TSS concentration reduction plays the dominant role on TSS load removal, that is, the main mechanism of TSS load removal by grassed swales is vegetation interception and particle sedimentation. However, TSS concentration removal of grassed swales is inefficient under high hydraulic load and low influent concentration, then the contribution of infiltration for TSS load removal become significant. For example, the ratio of TSS concentration removal of the POI swales is 2.80% at 8 m^3/h hydraulic load and 200 mg/L influent concentration, but the ratio of TSS load removal reaches 8.36%. The contribution of infiltration cannot be ignored. Meanwhile, it is clear that hydraulic load and initial concentration are also key factors for TSS load removal.

Further, due to low efficiency of runoff volume control by grassed swales (Fig. 5), the ratios of TSS load removal under different influent patterns are also similar. Compared with the efficiencies of TSS concentration removal and TSS load removal, only when the hydraulic load is 2 m^3/h, the ratio of the POI swales is slightly higher than others.

4. Conclusions

The performance and potential on TSS concentration removal, runoff volume reduction, and TSS load removal of laboratory-scale grassed swales is studied. The experiments are conducted under three influent patterns, three hydraulic loads, and three initial concentrations. According to the results of simulation experiences, the mean ratios of TSS concentration removal range from 2.8% to 42.3%. Hydraulic

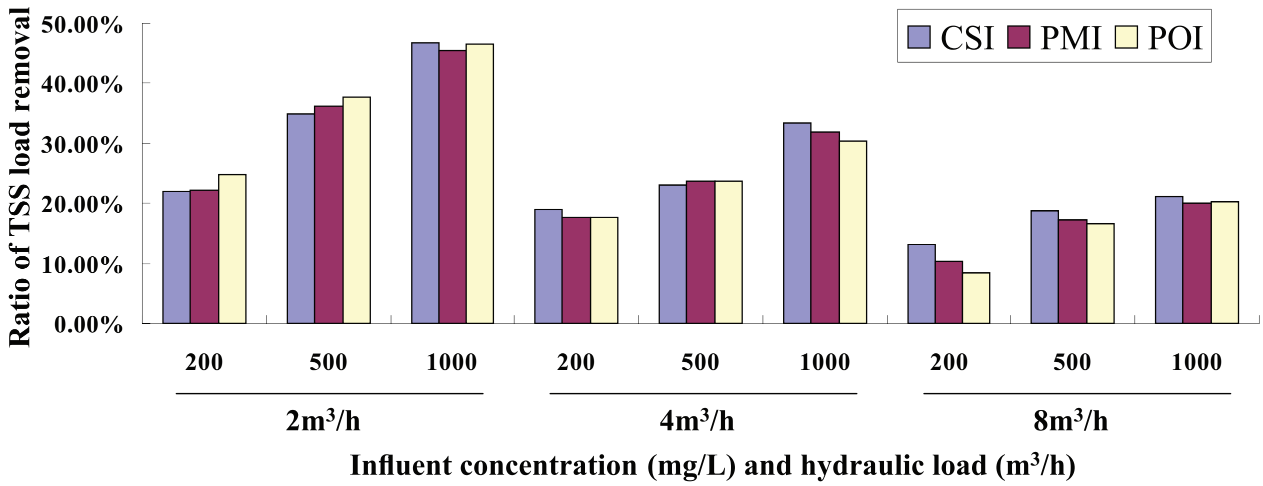

Fig. 6. The ratio of TSS load removal by grassed swales under different conditions.

load and initial concentration are the key factors for TSS concentration removal by grassed swales. Low hydraulic load and high initial concentration could result in the high performance for grassed swales. Mean runoff reduction rates of grassed swales range from 5.11% to 13.46%, which is influenced significantly by contact area (between the runoff and swales surface) and hydraulic residence time. The POI swales present better performance on runoff volume reduction than the CSI and PMI swales. The higher the hydraulic load, the more the similar runoff reduction efficiencies by grassed swales among three influent patterns. The mean ratios of TSS load removal by grassed swales range from 8.36% to 46.77%, which is contributed by the combined action of vegetation interception, particle sedimentation, and infiltration. The influent patterns of grassed swales have little influence on the efficiency of TSS load removal.

Acknowledgments

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