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Study on the purification capacity of rain garden paving structures for rainfall runoff pollutants

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Abstract: Rain gardens are one of the best measures for rainfall runoff and pollutant abatement in sponge city construction. The rain garden system was designed and developed for the problem of severely impeded urban water circulation. The rain gardens monitored the rainfall runoff abatement and pollutant removal capacity for 46 sessions from January 2018 to December 2019. Based on these data, the impact of rain gardens on runoff abatement rate and pollutant removal rate was studied. The results obtained indicated that the rain garden on the runoff abatement rate reached 82.5%, except with extreme rainfall, all fields of rainfall can be effectively abated. The removal rate of suspended solid particles was the highest, followed by total nitrogen and total phosphorus, the total removal rate in 66.35% above. The rain garden is still in the "youth stage", and all aspects of the operation effect are good.

Introduction

Rapid urbanization has led to a sudden increase in impervious surfaces and consequent increase in surface runoff (LI et al. 2008); this has seriously affected the urban water cycle process and increased the risk of urban flooding (Ghosh et al. 2018). With the promotion of sponge city construction, the concept of low impact development (LID) based on "infiltration, retention, storage, purification, use, and discharge" emphasizes the adoption of engineering measures to maximize runoff and its load of pollutants (Zhang et al. 2016). As one of the main forms of LID, rain gardens can effectively achieve the purpose of "infiltration, detention and storage" (Tang et al. 201, Hong et al. 2018, Wang et al. 2022, Gao et al. 2022).

Rain gardens are also known as bioretention ponds, submerged green spaces, biofiltration ponds, etc. (Hess et al. 2021, Kim et al. 2021.13.). The purpose of all of them is to effectively regulate the quantity and quality of water that sinks into the runoff by reducing pollutants through various plants, microorganisms, biological and physical properties of the medium, and filler voids (Luo et al. 2008, Sun et al. 2011). At this stage, the research on rain gardens are mainly focused on the retention capacity of runoff, the purification effect of pollutants carried by them, and the optimization of engineering design parameters (Jiang et al. 2012, Zhang et al. 2019, Gupta et al. 2018). Studies have shown that rain gardens can increase the infiltration of the rainwater, effectively recharge groundwater, and have a significant effect on the stagnation and abatement of runoff rainfall (Tang et al. 2012, Trowsdale et al. 2011, Davis et al. 2012). The pollutants in runoff sink into rain gardens, which have a better removal effect of solid suspended matter, oil and grease, heavy metals, total phosphorus, and other pollutants (Palmer et al. 2013, Chahal et al. 2016); and the influence of its structural type and internal environment, resulting in unstable purification effect of nitrogen and other elements (Li et al. 2014). The sink ratio area and filling mode of different areas (Tang et al. 2012) have different effects on runoff volume and pollutant concentration abatement (Guo et al. 2018, Ming et al. 2018), which also affects the operational life of rain gardens.

Rain gardens are gradually becoming one of the preferred measures for sponge city construction due to their features of ecological improvement, ease of management, relative independence and better effect on pollutants going out in runoff. However, most of the studies on rain gardens only focus on a certain area, aiming to provide some reference for the construction of sponge cities in the region. Based on this, the second batch of sponge city construction pilot areas approved by the state have been built in Pingxiang City. Take the rain gardens as the subject of study, the study of urban surface runoff into the rain garden after the long-term operational effect, analysis of the actual operation of the rain garden life, to provide technical support for the evaluation of the city's sponge city construction and the repair and maintenance of all types of built rain gardens.

Study area and methodology

Study area

The test site is located in the Housing and Urban-Rural Development Bureau, 98 Yuejin North Road, Pingxiang City, Jiangxi Province, geographically it is located at 113.852599 E and 27.646127 N. The test site is located in an area with an annual average rainfall of 1600 mm, an annual maximum rainfall of 2083.4 mm (1962) and an annual minimum rainfall of 1086.4 mm (1971), with concentrated rainfall from April to June. The unit implemented the sponge city construction project in advance in 2016, laying the foundation for Pingxiang City to build an innovative sponge city with Jiangnan characteristics. According to the sponge city construction program, the Construction Bureau built various forms of rainwater gardens biological retention ponds with a total area of 1050 m^2; the rain garden and its paving structure in the study area are shown in Figure 1. The rain garden started to operate in 2016 and receives mainly rainwater runoff from the roof and road. Combined with the rainwater pipe renovation, overflow pipes have been added in the rain gardens, and rainwater exceeding the storage capacity can overflow into the rainwater pipes. The rainwater exceeding the storage capacity will overflow into the rainwater pipe, and the purified rainwater from the rainwater garden will finally flow into the landscape pool of construction Bureau through the hidden pipe. Rainfall information was determined by the Yichun hydrology bureau set in Pingxiang City, Economic Development Zone of Tianzhong hydrology station. Pingxiang city rain garden site and structure design diagram is shown in Figure 1.

Research method

One of the goals of the construction of sponge city in Pingxiang City is that 75% of the total annual runoff was effectively controlled, i.e. , no runoff is generated when the daily rainfall is less than 22.8 mm; the water quality discharged to the model river reaches the requirements of Class III water bodies. Therefore, the rain garden is the focus of this study for the detention of runoff rainwater and its purification of carried pollutants.

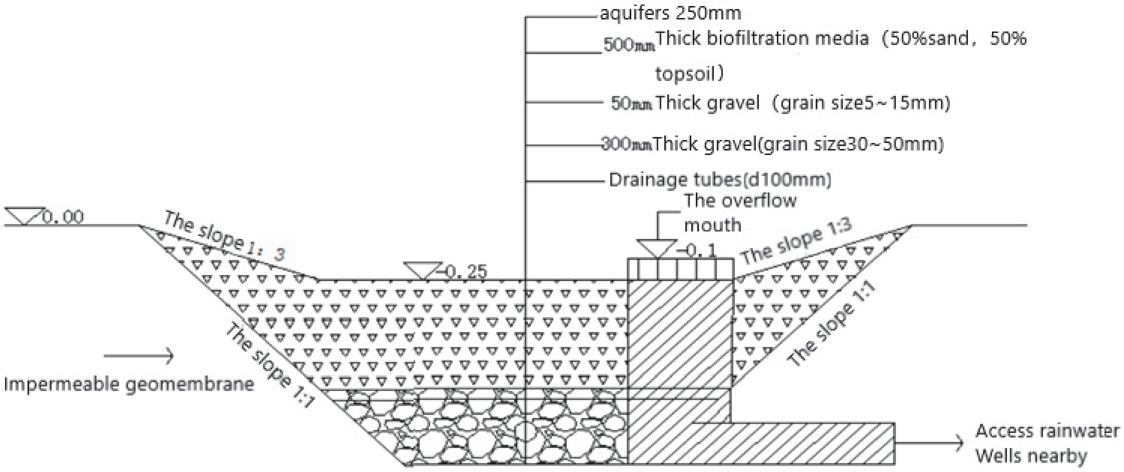
Analysis of runoff retention and abatement capacity

The rain water garden was equipped with overflow facilities. In order to study the filtering effect of the rain garden on the pollutants in runoff rainwater, an outlet was installed under the road surface of the rain garden to collect the filtered water samples from the rain garden. The retention and reduction effect of the rain garden on runoff rainwater is reflected by the reduction rate (Rv), which can be expressed as:

$$R_v = \frac{Q_{in} - Q_{out}}{Q_{in}} \times 100\% \qquad (1)$$

where Q_{in} and Q_{out} are the total amount of inflow runoff and overflow runoff (L), respectively.

a. Actual site view of the rain garden



b. Rain garden structure design pavement drawing

Fig. 1. Site and structural design drawing of Pingxiang Rain Garden

Based on the flow process monitored by the rainfall process, the inflow and outflow Vi are calculated to obtain the total inflow or outflow Q at a certain moment.

$$Q = \sum_{i=1}^{n} V_i \Delta t_i \quad (2)$$

Pollutant purification capacity analysis

Surface runoff water quality monitoring indicators such as total nitrogen (TN), total phosphorus (TP), suspended solids (SS), etc. The monitoring method refers to the "Analytical Methods for Water and Wastewater Monitoring (4th Edition)". The removal efficiency of rain gardens for pollutant loads is characterized by RT, calculated as

$$R_T = \frac{T_{in} - T_{out}}{T_{in}} \times 100\% \quad (3)$$

where Tin and Tout are the pollutant loads in inflow and infiltration runoff, respectively (mg).

Data collection

The experimental monitoring started in January 2018 and ended in December. Due to the effectiveness of rainfall and weather factors, samples were not collected for all fields of rainfall during the monitoring period that lasted for 2 years; the characteristics of the effective rainfall fields collected are shown in Table 1. Through the automatic flowmeter installed at the entrance and overflow pipe of the rain garden, the instantaneous rainfall inflow and outflow of each field were recorded, and through the homemade automatic sampling system, water samples were collected at the import and export, and sent to the water quality testing center of Yichun Hydrology Bureau of Jiangxi Province for monitoring. The rainfall characteristics of Pingxiang in 2018 are shown in Table 1. The rainfall characteristics of Pingxiang in 2019 are shown in Table 2.

Results and Analysis

Rain gardens on runoff abatement capacity analysis

The reduction effect of the rain garden in Pingxiang Construction Bureau on multiple rainfall runoff from 2018 to 2019 is shown in Figure 2. From the figure, it can be seen that the rain garden has a strong reduction ability on rainfall runoff. In 2018, the 20 rainfall-runoff reduction rates were all above 90%, and 90% of runoff was stagnated without overflow. In 2019, the reduction

Table 1. Rainfall characteristics of Pingxiang in 2018

Rainfall extension time	Rainfall [mm]	Duration of rainfall [d]	Antecedent Dry Period [d]	Rainfall extension time	Rainfall [mm]	Duration of rainfall [d]	Antecedent Dry Period [d]
2018/2/24-2/26	20. 5	3	19	2018/6/24-6/25	20. 0	2	1
2018/3/4-3/7	45. 5	4	4	2018/7/11-7/12	55. 0	2	1
2018/3/13-3/15	29. 0	3	5	2018/8/25-8/27	29. 0	3	9
2018/3/17-3/19	31. 5	3	1	2018/8/30-8/31	44. 5	2	2
2018/3/24-3/25	24. 0	2	2	2018/9/3-9/6	43. 5	4	2
2018/4/11-4/14	53. 0	4	5	2018/10/13-10/16	49. 0	4	3
2018/4/21-4/22	41. 5	2	6	2018/11/9-11/11	44. 5	3	1
2018/5/4-5/7	26. 5	4	1	2018/11/14-11/15	45. 0	2	2
2018/5/30	29. 5	1	2	2018/11/19-11/20	30. 5	3	3
2018/6/20-6/22	22. 0	3	12	2018/12/8-12/10	26. 5	3	1

Table 2. Rainfall characteristics of Pingxiang in 2019

Rainfall extension time	Rainfall [mm]	Duration of rainfall [d]	Antecedent Dry Period [d]	Rainfall extension time	Rainfall [mm]	Duration of rainfall [d]	Antecedent Dry Period [d]
2019/1/1-1/4	38. 5	4	19	2019/5/18-5/19	65. 5	2	2
2019/1/10	24. 5	1	1	2019/5/26-5/27	22. 0	2	5
2019/2/17-2/18	43. 5	2	1	2019/6/6-6/8	116. 5	3	4
2019/2/20	22. 5	1	1	2019/6/22	73. 5	1	6
2019/2/26-2/28	20. 0	3	1	2019/7/3	51. 0	1	1
2019/3/4	25. 5	1	1	2019/7/6-7/7	110. 5	2	2
2019/3/21-3/24	55. 5	4	1	2019/7/8	215. 5	1	1
2019/3/31-4/4	64. 0	5	2	2019/7/11-7/12	53. 5	2	1
2019/4/9-4/10	20. 5	2	4	2019/7/14	21. 0	1	1
2019/4/13	21. 0	1	2	2019/7/18-7/29	39. 0	2	2
2019/4/18-4/19	30. 5	2	1	2019/8/9-8/10	21. 0	2	11
2019/4/21-4/24	65. 0	4	1	2019/10/25-10/27	30. 0	3	2
2019/4/26-4/30	25. 0	5	1	2019/12/18-12/21	48. 0	4	16

capacity of 26 records was not completely consistent with 24 of them up to 85%. The other two with lower reduction rates were recorded on July 7 and July 8, respectively, with reduction rates of 68.9% and 61.5%, respectively. The two rainfall times were similar and the rainfall was high, 110.5 mm on July 7 and 215.5 mm on July 8. As a result of the short rainfall and interval time, the pores in the pavement layer of the rain garden tended to be saturated, and the infiltration rate reached a stable infiltration state. At this time, the stagnant runoff capacity of the rain garden was weakened, and the reduction rate decreased accordingly.

The Pingxiang city people's government prepared "Pingxiang city sponge city construction pilot city implementation plan (2015–2017)". One of the general objectives of this plan is to effectively control 80% of the total runoff, corresponding to the design of the daily rainfall of 27.1 mm. The annual rainfall can be effectively abated. Pingxiang City Construction Bureau rain garden run two years in the process, the rainfall runoff on 46 occasions completely abate rate reached 82.5%, reached the design goal. In addition to extreme rainfall conditions, its abatement rate are relatively stable and durability is good, rain garden concave depth and larger pore pavement structure can stagnate a larger amount of runoff (Tang et al. 2015), indicating that this pattern pavement structure of rain gardens on runoff rainfall abatement stagnation effect is better. Rain gardens on runoff abatement rate is shown in Figure 2.

Effectiveness of rain gardens in removing pollutants from rainwater runoff

Removal effect on TN

Figure 3 shows the TN concentration in runoff and the TN concentration and the removal rate after infiltration into the rain garden. The TN removal rate in the runoff of the rain garden exceeded 70% for two years. Overall, the removal rate in 2019 was lower than in 2018. The removal rate was related to the TN concentration in a runoff, rainfall, and the number of preceding sunny days (Jiang et al. 2012, Boogaard et al. 2015), with the lowest removal rates of TN in rainfall runoff for the two sessions of August 25–27, and October 13–16, 2018, at only 74.5% and 73%. Since the initial concentration of TN at the two stations was no less than 8 mg/L and the duration of rainfall at the two stations was 3 d and 4 d respectively, TN in runoff was different (Tang et al. 2015). The dissolved TN was nitrified and denitrified in the anaerobic environment of the rain garden for a long time. Runoff entering the rain garden later flusher it, resulting in a low runoff removal rate

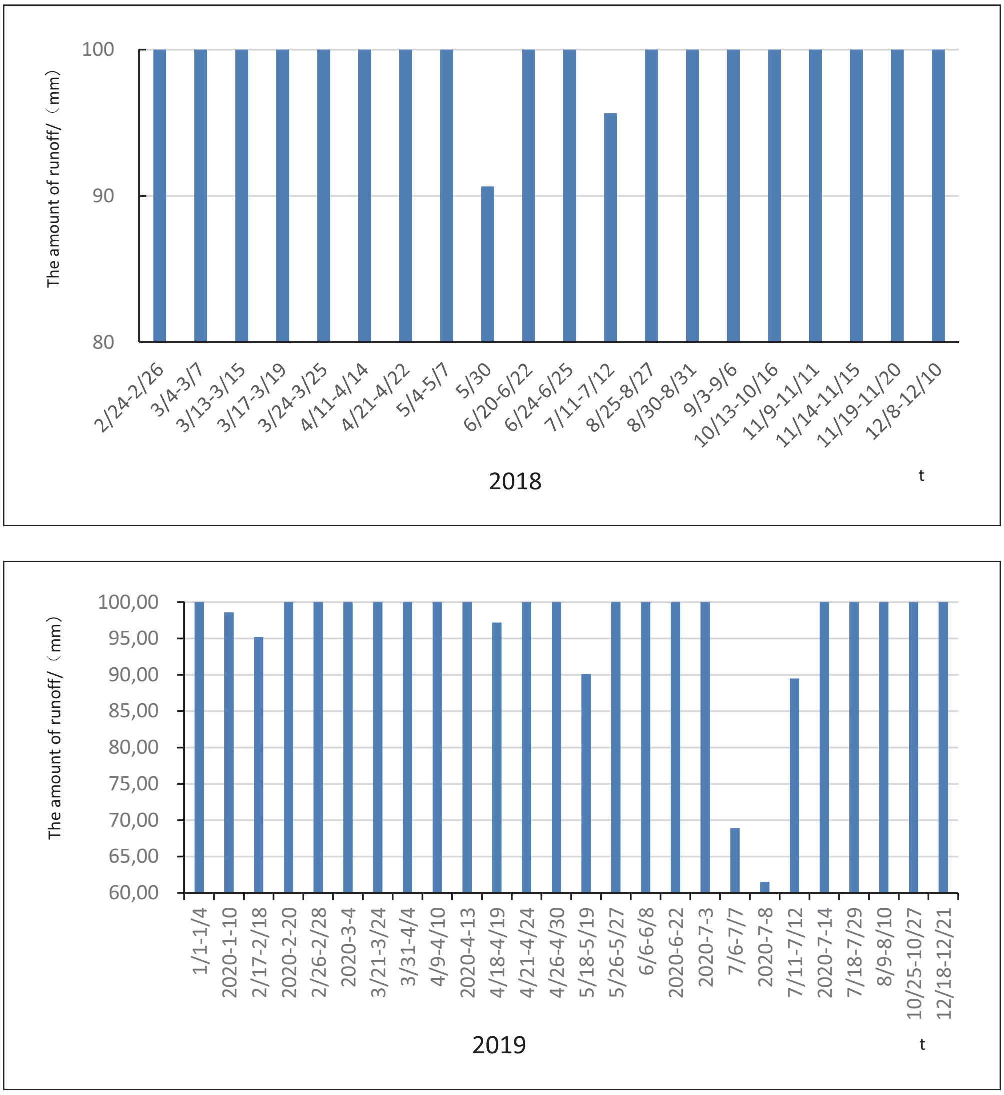


Fig. 2. Runoff reduction rate of rainwater garden

in the two sites. The average removal rate of runoff pollutants from rain gardens in 2019 was lower than that of 2018, and there are 5 fields with removal rates below 75%. The lowest runoff removal rate of this field was only 72.26% on July 8, which occurred before the rainfall on July 6–7, and the rainfall amount reached 110.5 mm. due to the larger intensity of rainfall resulting in the pavers in the rain garden being in a saturated state. On July 8, the rainfall was 215.5 mm, reaching the level of heavy rain. After entering the rain garden, the rain runoff quickly filled the pore space of the road surface, and moved from the surface of the rain garden to the bottom under the action of capillary connectivity. This relatively fast hydraulic process led to a short residence time of rainfall runoff in the rain garden. When the ability of the rain garden to intercept the pollutants is reduced, TN removal rate of the rain garden is easy to be too low. The TN removal rate of rain gardens in rainfall-runoff is shown in Figure 3.

Removal effect on TP

Figure 4 shows the removal ability of rain gardens of Pingxiang City Construction Bureau on TP in rainfall runoff, and it can be seen from the figure that the removal rate of TP in rain gardens on rainfall runoff in both years was above 65%. Studies have shown that phosphorus in rainfall runoff exists mainly in particulate form (Tang et al. 2015); TP that sinks into rain gardens migrates mainly with the movement of runoff within the paved body. As seen in Figure 1(b), the rain garden paving of Pingxiang City Construction Bureau presents a structural pattern of fine on top and coarse on the bottom, with small porosity of the upper material and capillary aggregation, and this paving structure has a good filtering effect on the runoff that sinks into it. The phosphorus in the granular state is retained or accommodated within these pores, and the longer the number of sunny days, the more space vacated and the better the removal of TP. It has been shown that various types of bioretention measures can capture the vast majority of particulate phosphorus (Morales et al. 2009). From August 25 to 27, 2018, which had as many as 43 sunny days, a runoff TP concentration was 1. 86 mg/L, which was higher than the annual average of 1.61 mg/L, but, a removal rate of TP was 93.5%. However, the TP removal rate was only 66.35% during the rainfall period of July 8, 2019, and the effect of the pore was

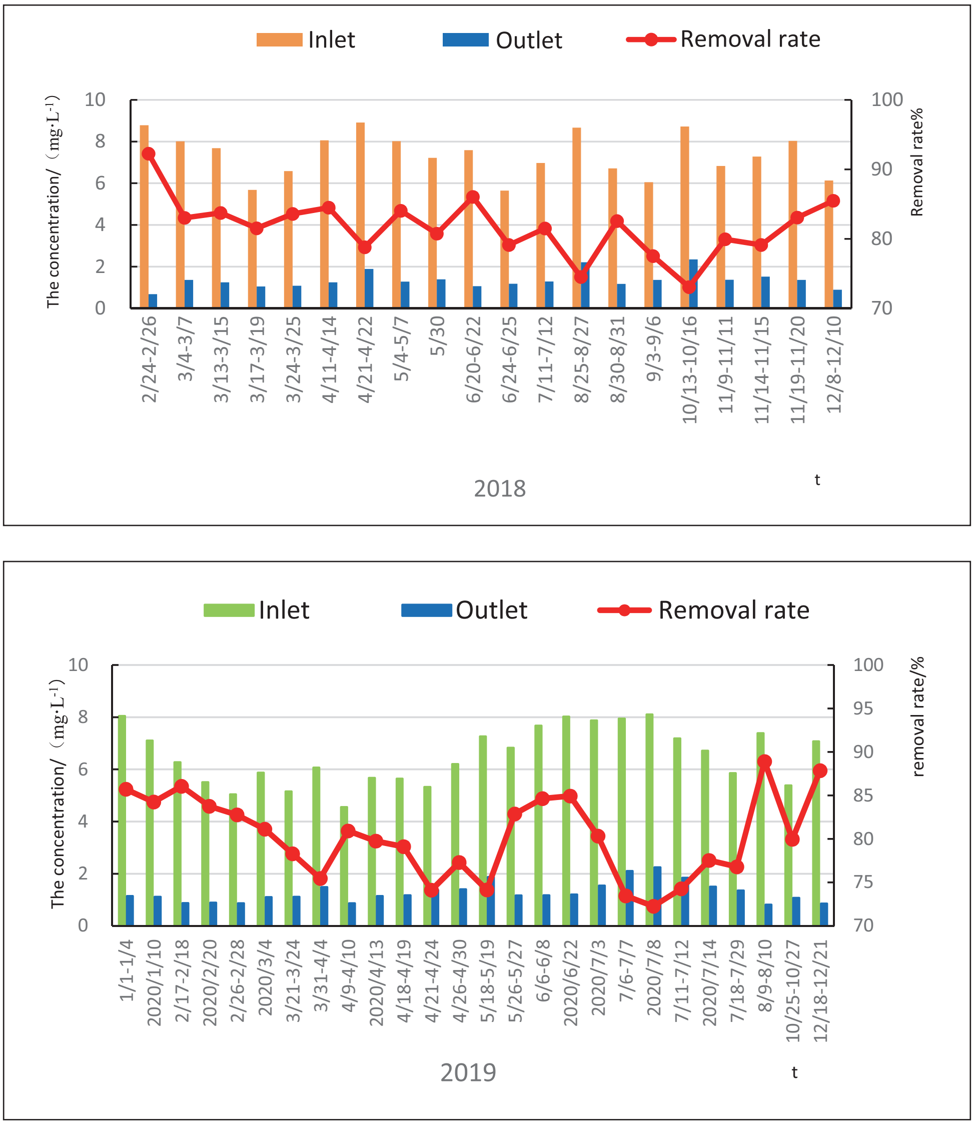


Fig. 3. TN removal rate of rainfall runoff from rainwater gardens

greater after flooding. The fine particles in the rainfall runoff discharged TP directly into the bottom ditch through the rain garden system, which indicated that the number of sunny days and rainfall intensity had a great impact on the TP removal rate in the early stage.

The removal rate of TP in rainfall runoff was above 75% for all fields in FY 2018 and 65% in FY 2019; this was also higher than the removal rate of TP in similar rain gardens abroad (Hsieh et al. 2005), but the removal rate showed a decreasing rate year by year. The removal rate of TP in rainfall runoff by rain gardens is shown in Figure 4.

Removal effect on SS

Figure 5 shows the removal effect of rain gardens of Pingxiang City Construction Bureau on SS in rainfall runoff, as revealed in the picture, the removal rate of SS is high, above 85% in both years, and most of the particles in the runoff are detained and retained in the rain gardens. The fine dispersed suspended solids particle size in rainfall runoff ranged from 0.1 to 1.0 μm, and the coarse dispersed suspended solids particle size was larger than 1.0 μm (Jeong et al. 2020), 33.8% of TP and 13.6% of SS in rainfall runoff from the July 8, 2019 were not retained by the rain gardens and discharged directly to the outlet, and the capillary pressure within the rain gardens after being soaked therein carried the fine dispersed suspended solids particles to the drainage outlet. It means that TP in rainfall runoff in Pingxiang City is mainly attached to finely dispersed suspended solids, and the compactness of the paving structure should be improved to increase the interception capacity of tiny particles in the process of rain garden construction. The removal rate of SS in rainfall runoff by rain gardens is shown in Figure 5.

Pingxiang City Construction Bureau rain garden functional benefit analysis

The chief functions of rain gardens is to abate runoff and remove pollutants in the sponge city construction. According to the pavement structure, rain gardens can be divided into drainage type, infiltration type and the mixed type (Guo et al. 2015), A, comparative analysis showed that the rain gardens within the Pingxiang City Construction Bureau belong to the mixed type. The ability of rain gardens to abate runoff

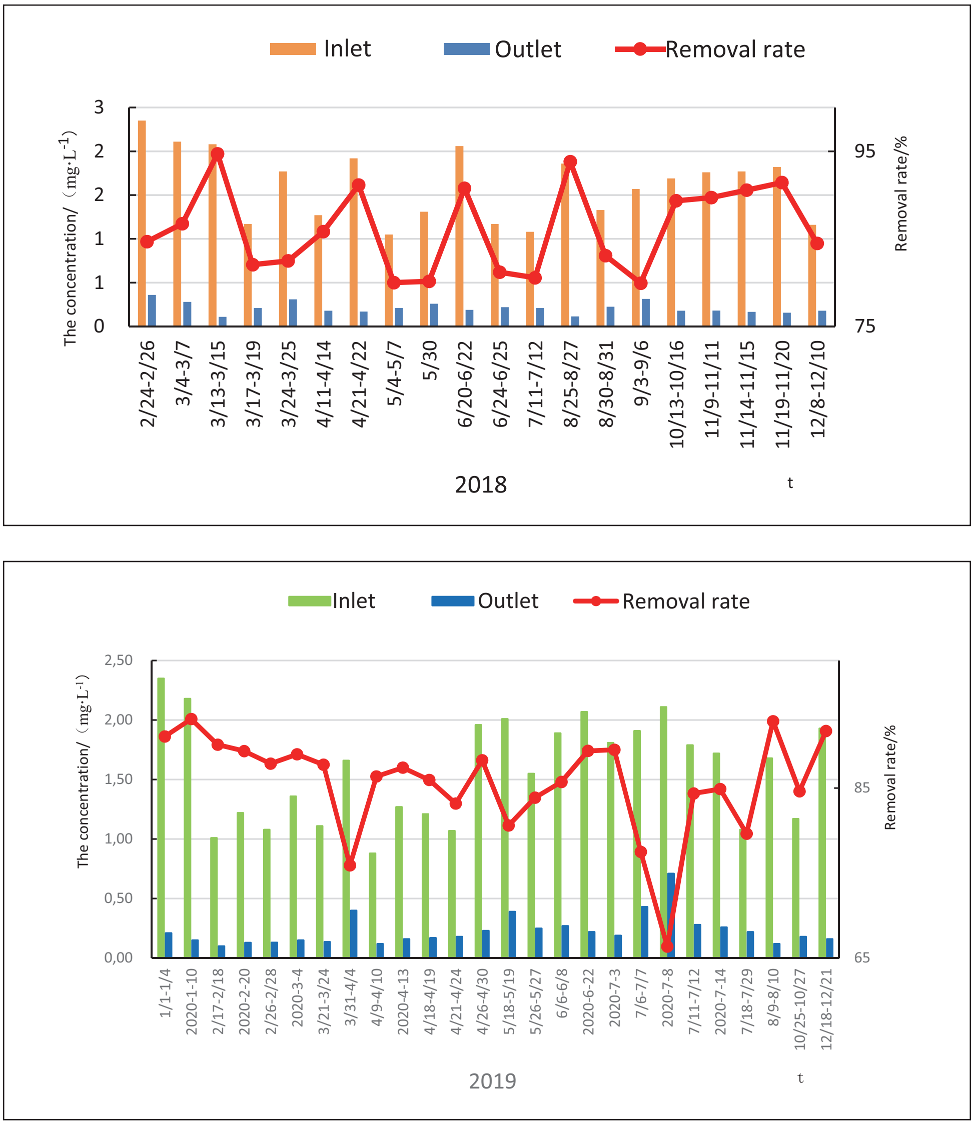


Fig. 4. TP removal rate of rainfall runoff from rainwater gardens

is influenced by the infiltration capacity and porosity of the paving materials; , more pores can stagnate and accommodate part of the runoff, and when all the pores are filled with runoff, the capillary hydraulic conductivity becomes effective and transports the runoff into the deep soil body. Particulate matter in the runoff is the main cause of pore-clogging in rain gardens. When the pores in the rain garden system become blocked, the conductivity of the capillary water decreases. The function of the rain garden will gradually disappear until the permeability is completely lost.

During the 2 years of operation of the rain garden in Pingxiang Construction Bureau, the 22.5 mm/day rainfall was effectively alleviated. Except for the special rainstorm, the abatement rates of other rainfalls were above 85%, which indicates that the function of the rain garden to alleviate rainfall and runoff had been well performed. This is also with the rain garden running years is relatively short, its long-term operation effect to be further monitoring analysis. To extend the service life of Pingxiang City sponge city rain garden, for this kind of rainfall frequently, rainfall hilly areas to strengthen the usual operation maintenance, timely removal of surface layer silt, conditional cases can surface pavement structure for replacement, as well as reduce urban road dust accumulation, etc. is the rain garden long run guarantee.

Pingxiang City Construction Bureau rain gardens on rainfall runoff TN, TP, SS removal average value of 81%, 85.87%, 90.5%, respectively, on these three pollutants removal range of 92.25% to 72.26, 94.32% to 66.35%, 95.06% to 85.63%, which TP removal rate of the largest variation. The pollutant removal capacity of the Bureau of Construction rain garden during the study period exceeded that of rain gardens of the same type (Li et al. 2014, Zhang et al. 2019), and according to the classification of stage purification capacity, the rain garden belongs to the "young stage" (Guo et al. 2015). At this stage, rain gardens within the paved body media pore larger, plant and microbial communities are in the growth period, the adsorption and dissipation of pollutants are also strong. With the increase of operation years, the accumulation of pollutants in the pores of the media will breed and reproduce more pollutants after not being cleaned and will be brought to the drainage outlet after being showered by the upper incoming water, causing secondary hazards to the receiving water body. Effective control of pollutants in runoff from the source, as well as the combination of various sponge city construction

Fig. 5. The SS removal rate of rainwater gardens in rainfall runoff

measures in the "sponge body", unified and sequential rainfall runoff stagnation and abatement, can improve the life of rain gardens and other "sponge body". The life span of rain gardens and other "sponge bodies" can be improved.

Conclusion

1. By monitoring and analyzing the operation of the rain garden in 2018 and 2019, we know that the rain garden on the control target rainfall (daily rainfall 22.5 mm) can be completely abated and it meets the design requirements such as rain garden on the rainfall runoff abatement and rainfall intensity, duration, the number of pre-sunny days and rain garden running time.
2. The removal rate of TN, TP and SS in rainfall runoff from rain gardens ranged from 66.35% to 95.06% during the test period, and the removal rate of SS was the highest. However, fine suspended solids can carry a large amount of TP, this part of SS is not easy to be intercepted and retained by rain gardens. Continued longer rainfall process resulting in rain garden paving body capillary hydraulic conductivity effect highlights, reduce the effect of pollutant retention, increase the ability to rainfall runoff abatement.
3. Pingxiang city construction bureau rain garden is in the "youth stage", running process in all aspects of the function goes well, at present the overall reached the design objectives.

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