Analysis of Rainfall Runoff Pollution and Split-Flow on Urban Pavement

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Abstract: The pollution situation and the variation characteristics of the water quality of rainfall runoff in urban area were analyzed. Water quality monitoring results indicated that, during the early period of rainfall, the maximum concentrations of suspended solid, chemical oxygen demand, ammonia nitrogen and total phosphorus in the water on the urban pavement reached 410 mg/L, 282.4 mg/L, 11.18 mg/L and 1.2 mg/L, respectively. This means that the initial rainfall runoff pollution is serious. Additionally, with the increase of rainfall duration, the pollutant concentration gradually decreased and stabilized eventually. Finally, the engineering simulation experiment of split-flow of the initial rainfall showed that the reduction rate of chemical oxygen demand, total phosphorus, suspended solid, and ammonia nitrogen on the pavement rainfall could reach 48.15%, 51.77%, 56.91% and 33.45% when the amount of initial rainfall split-flow was 3 mm. Based on the field observations and theoretical analyses, the initial rainfall discarding strategy is recommended as a primary treatment of rainfall reuse system to improve water quality under different rainfall patterns. These findings are vital for the rainfall utilization in the construction of Sponge City Project.

1 INTRODUCTION

In recent years, the urban water logging and drinking water pollution caused by emergencies have occurred frequently. Rainfall could be used as drinking water resource or alternate source in case of sudden pollution. Some developed countries such as Germany (Thilo and Uwe, 1999), the United States and Japan (Wang et al., 2011) attach great importance to the recycling of rainfall; they have carried out the rainfall utilization project and formulated a series of policies and regulations, and also established a relatively perfect system of rainfall utilization (Zhao and Niu, 2001). Compared with the developed countries abroad, rainfall quality in China is obviously poorer. It is due to the serious air pollution and the scouring of the atmosphere in the process of rainfall. And there are still many deficiencies in China's rainfall resource utilization and management system. Therefore, China has put forward the construction of "sponge city".

Zhenjiang City has made certain achievements on district transformation as well as waterfront park construction based on the low impact development concept (Wang et al., 2014). The population in university is dense and the domestic water demand of university is great. Therefore, the trial of rainfall collection and utilization in universities can effectively reduce the water pollution caused by anti-emergencies. It can also make more effective designs and modifications on the transformation of the original conditions (Zhao, 2012). Based on the new campus of Jiangsu University, this paper analyzed the water quality characteristics of rainfall runoff on pavement and carried out the engineering simulation of split-flow. And this research provided basic data and technical support for pavement surface rainfall utilization.

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Table 1: Campus rainfall and monitoring time.

number	Monitoring date	early sunny days (day)	Pavement runoff time	Rainfall duration (min)	Rainfall amount (mm)	Rainfall intensity (mm/min)
1	2017.5.29	2	10:45	76	1	0.013
2	2017.6.16	1	14:23	155	11.7	0.075
3	2017.6.25	4	15:57	20	4	0.200
4	2017.7.6	3	8:56	390	6	0.015
5	2017.7.16	5	8:51	300	8	0.027
6	2017.8.7	12	16:20	60	1.5	0.025
7	2017.8.8	1	17:00	64	16.9	0.264
8	2017.8.20	1	18:59	42	2.8	0.067
9	2017.9.29	4	8:31	50	1.1	0.022
10	2017.11.12	5	11:21	>480	18.5	<0.039

2 MATERIAL AND METHODS

2.1 Sampling

A double-edged fine-toothed comb on the ground in front of the library of Jiangsu University was taken as a sample site to analyze 10 times of different rainfall. When the rainfall on the road formed runoff, we collected the runoff and started the timing. We took some sample at regular intervals and recorded time of each sample based on the rainfall intensity. The initial sample interval of runoff was short. With the increase of rainfall duration, the sample interval gradually increased. Table 1 shows the rainfall monitoring information.

2.2 Determination of Indicators

In general, the pollutants in rainfall are mainly suspended matter, organic pollutants, nitrogen, phosphorus and other nutrient elements. Thus suspended solid (SS), chemical oxygen demand (COD), ammonia nitrogen (NH_3-N) and total phosphorus (TP) were determined as the indicators and analyzed.

SS is an important index for evaluating the sensory properties and pollution of water body, and SS concentration is determined by weighing method. COD indicates the relative content of organic matter in water, and is determined by dichromate oxidation method. NH_3-N is a nutrient in water and can cause water eutrophication. It is the main oxygen consumption pollutant in water. Concentration of NH_3-N is determined by nessler's reagent colorimetric method. TP is the main factor of eutrophication in water body to evaluate the degree of water pollution. And TP concentration was measured with ultraviolet-visible spectrophotometry after potassium persulfate digestion at 121℃ for 30 min.

2.3 Experiment of Initial Split-Flow on Pavement

Sansalone et al. (1997) proposed that the pollution load of 20% of the initial rainfall runoff accounted for 80% of the total rainfall in the study of road runoff. In the research on initial split-flow on pavement rainfall, He Junchao (2015) and others pointed out that when the runoff ratio was about 30% to 40%, the corresponding proportion of pollution load was about 42% to 70%. Chew (he et al., 2004) and others found that under the conditions of the rainfall intensity being 0.1 mm/min, the pollution load in the initial 20 minutes accounted for 42% of the whole rainfall, and the pollution load in later 20 minutes only accounted for 10%. It could be seen that the pollutants in the runoff were mainly concentrated in the initial runoff. Therefore, rainfall in the early stage was supposed to be discarded, and then the rainfall could be collected, stored, treated and reused.

The main purpose of the initial discarding is: (1) To avoid bringing a large amount of sediment into the rainfall treatment structure, and to reduce the difficulty of cleaning and maintenance at the later stage; (2) To protect the rainfall storage and to ensure that the rainfall quality in the later treatment process is relatively stable; (3) To avoid collecting and treating the rainfall which is in very small amount with high pollution, and to protect storage structures and subsequent treatment equipment (Liu and Fu, 2004).

2.4 Initial Split-Flow Calculation

Because the initial rainfall split-flow is affected by many factors such as the nature and size of the catchment, the degree of pollution, the subsequent treatment system and the balance of water flow, there has not been a unified formula so far. This paper determined the actual split-flow according to the pollutant load needed to control.

Some scholars (Charbeneau and Barrett 1998; He, 2011) have found an exponential relationship between pollutant concentration and cumulative runoff in rainfall, and the following relations are given:

$$C_t = C_0 e^{-K_h \cdot h} \tag{1}$$

Where C_t is the concentration of contaminant in runoff as runoff starts t minutes, mg/L. C_0 is the pollutant concentration in rainfall as runoff forms, mg/L. K_h is the comprehensive scouring coefficient with rainfall as the variable. And it is related to the surface water quality, rainfall intensity and pollutant trait, mm^{-1}. h is the cumulative rainfall within t minutes of runoff, mm.

$$Y_0 = \int_0^H C_t dh \tag{2}$$

$$Y_c = \int_0^h C_t dh \tag{3}$$

Where H is the total rainfall. C_0 is the concentration of pollutants in the rainfall. As the runoff starts for t minutes, the pollutant concentration is C_t. Y_c is the pollution load of the runoff of different rainfall. Y_0 is the total runoff pollution load generated by rainfall.

$$L = \frac{Y_c}{Y_0} = \frac{\int_0^h C_t dh}{\int_0^H C_t dh} = \frac{1 - e^{-K_h \cdot h}}{1 - e^{-K_h \cdot H}} \tag{4}$$

Where L is the pollutant migration rate during the runoff scouring process. It is also known as pollution load rate.

3 RESULTS AND DISCUSSION

3.1 Variation of SS Concentration in Rainfall Runoff on Pavement

Figure 1 shows the variation of SS concentration in the pavement rainfall with the rainfall duration. The concentration of SS decreased sharply in the early stage of rainfall, and then decreased slower. After 20-30 minutes, the precipitation of SS was basically below 30 mg/L, which met class VI surface water standards (GB3838-2002). As shown in Table 1, the amount and intensity of rainfall were small and the rainfall time was short on May 29. Hence, the overall curve of SS concentration was high, and it fluctuated. Comparing the two times of rainfall on June 16 and June 25, we could find that the decline trend of SS concentration curve on June 25 was steeper than on June 16 in the first 5 minutes. With the increase of rainfall duration, the stabilization trend of SS concentration on June 25 was faster. Therefore, the greater the intensity of rainfall was, the stronger the effect of scouring and dilution to contaminants was.

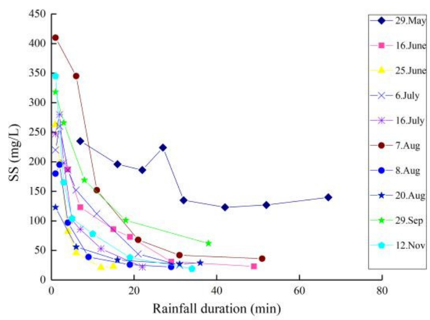

Figure 1: Pavement rainfall SS process along with the change of rainfall duration.

3.2 Changes of Cod Concentration in Rainfall Runoff on Pavement

Figure 2 shows the relationship between the rainfall COD concentration and the rainfall duration. It could be seen that the initial concentration of COD in rainfall runoff was high. The concentration of COD decreased significantly in initial 10 minutes. Then the concentration of COD was basically below 20 mg/L after 20 minutes. In contrast of the number of early sunny days before the two times of rainfall on August 7 and August 20, it was found that the longer the interval between the two times of rainfall was, the higher the concentrations of the initial rainfall contaminants were. It indicated that the pollutants would accumulate over time.

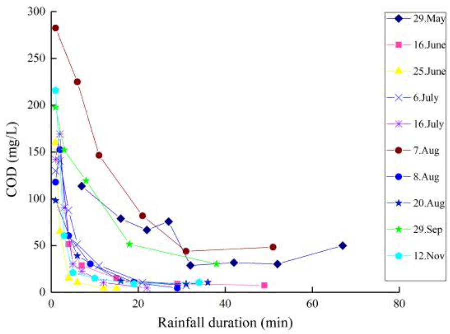

Figure 2: Pavement rainfall COD process along with the change of rainfall duration.

3.3 Variation of Ammonia Nitrogen Concentration in Rainfall Runoff on Pavement

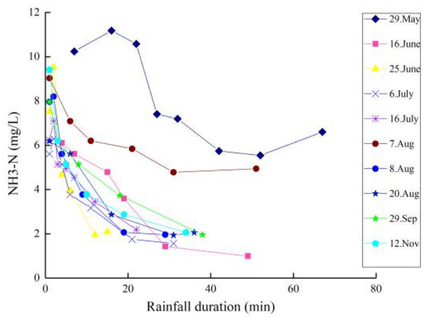

Figure 3: Pavement rainfall NH3-N process along with the change of rainfall duration.

Figure 3 shows the relationship between rainfall ammonia nitrogen concentration and rainfall duration. It could be seen that there was a significant downward trend of ammonia nitrogen concentration in runoff at the beginning, and then the ammonia concentration tended to be stable. Similarly, when the rainfall duration was short, and rainfall intensity was very small, the road surface runoff ammonia nitrogen concentration curve was high. In addition, the descending rate of early ammonia nitrogen concentration was very fast, then the descending rate gradually slowed down, and finally it tended to be stable.

3.4 Variation of TP Concentration in Rainfall Runoff on Pavement

Figure 4 shows the relationship between the rainfall TP concentration on the pavement and the duration of the rainfall. It could be seen that the concentration of TP in rainfall runoff dropped sharply in 0-10 minutes. Then the curve tended to be gentle after 20 minutes. Compared with the curve of August 8, the curve of August 7 was significantly higher. It was because the interval was 12 days. Additionally, the temperature of summer was high and there was no staff pouring the road. So when it began to rain on August 7, the TP concentration of initial rainfall runoff was up to 1.2 mg/L. With the process of the rainfall, TP concentration gradually decreased, but it was still higher than the concentration in other rainfall. It was because the rainfall intensity on that day was very small. Furthermore, the TP concentration on August 8 significantly decreased after the scouring. Thus, the initial concentration of rainfall runoff pollutants was low, and the concentration of pollutants during the final stabilization process was also low. Above all, the time required to stabilize was short.

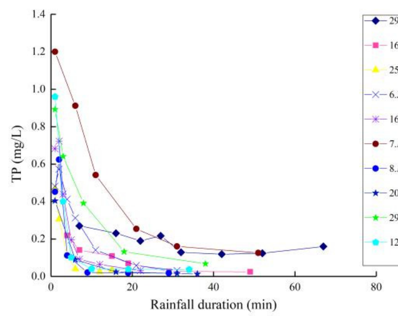

Figure 4: Pavement rainfall TP process along with the change of rainfall duration.

3.5 Determination of Split-Flow in Rainfall Runoff

The initial scouring of COD and SS of pollutants in rainfall runoff was the strongest, which indicated that the pollution load transferred by the initial runoff was the largest. Thus, the migration rate of COD and SS were used to determine the split-flow.

As shown in Figure 5, the COD and SS concentrations in the initial runoff were high on June 16, 2017. With the accumulation of rainfall, the COD and SS concentrations gradually decreased.

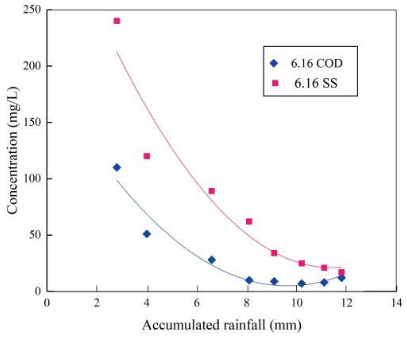

Figure 5: COD, SS scour curve of road runoff.

The curve-fitting expressions of COD and SS were $y = 171.23e^{-0.2789x}$ and $y = 479.57e^{-0.2817x}$, respectively, and they were consistent with the general relationship between the change of pollutants and the cumulative rainfall shown in equation (1). The correlation coefficient R^2 of the measured curve and the fitting curve that reflected the variation of COD_{cr} concentration during the rainfall was 0.8418, and the correlation coefficient R^2 concerning the variation of SS during the rainfall was 0.9645. And the fitting degree was good, which indicated that the main pollutants in the road rainfall runoff and the cumulative rainfall were exponentially related.

According to equation (4), the pollutant loading rate of COD and SS were calculated, and the pollutant loading rate L was expressed by the arithmetic mean of them. Table 2 lists the relationship between the loading rate of main pollutants and the rainfall amount.

Table 2: Relationship between main pollutant loading rate of road runoff and rainfall.

Rainfall amount (mm)	1	2	3	4	5	6	7	8	9	10
Road pollutant loading rate (%)	25.4	44.6	59.1	70.1	78.3	84.6	89.3	92.9	95.6	97.6

It could be seen from Table 2 that the pollution load rate in the initial runoff flow with the amount of 1 mm is 25.40%. With the accumulation of rainfall, the pollution load rate gradually increases, but the increasing rate decreases. When the amount of the rainfall reaches 3 mm, the pollutant loading rate is about 60%. Therefore, when the initial rainfall is discarded, the pollutant loading rate is about 60%.

Some studies have pointed out that the pollutants in pavement runoff are strongly affected by the previous number of sunny days (Li et al., 2008). It could be seen from Table 1 that the rainfall on June 16 was only one day from the last rainfall, indicating that the accumulation of pollutants was relatively slow. In addition, the proportion of contaminants in the initial runoff was large (Ding et al., 2011). Hence in the demonstration area, if the amount of the initial split-flow on pavement surface is 3 mm, this scheme could remove more than 60% of the pollutant load in the same rainfall intensity, which met the requirement of Zhenjiang Sponge City Construction Project. It could also alleviate the burden on subsequent rainfall treatment facilities. In summary, the amount of initial split-flow at the demonstration site has been designed to be 3 mm.

3.6 Simulation of Initial Discarding Engineering

The object of the simulation was selected at a rainfall outlet on the ground in front of the library of Jiangsu University. And two times of rainfall on January 3 and January 4 were discarded. The rainfall runoff area was about 400 m^2, and the split-flow volume was designed to be about 1.2 m^3.

Table 3. Changes of water quality in the engineering simulation test of initial rainfall discarding.

Date	Water Sample	COD (mg/L)	NH_3-N (mg/L)	TP (mg/L)	SS (mg/L)
2018.1.3	Sample 1	51.51	5.614	0.109	86
	Sample 2	39.39	3.736	0.054	46
2018.1.4	Sample 3	81.82	5.842	0.141	123
	Sample 4	42.42	4.788	0.068	53

In this experiment, the runoff rainfall flowing through the rainfall port was collected into the split-flow vessel by laying a tarpaulin at the selected rainfall port, and the rainfall characteristics were recorded synchronously within a rainfall tank. The pavement was made of impervious material like asphalt and tiles. Therefore, once runoff formed on the road surface, the runoff could be replaced by the rainfall. After the formation of the runoff, and the amount of rainfall recorded within the rain barrel reached 3 mm, it was deemed that the amount of the runoff reached 3 mm which was the amount of preset split-flow. Then we closed the inlet of the container and marked the road surface rainfall with chlorine bottles as the water sample 2. The initial split-flow in water containers was marked as the water sample 1. Table 3 shows the pollutant concentrations of two water samples.

According to the calculated formula of the pollutant reduction rate:

$$Reduction.rate(\%) = \frac{C_0 - C_e}{C_0} \times 100 \quad (5)$$

The results show that the reduction rates of COD in the initial rainfall runoff could reach 23.53% and 48.15%, the reduction rates of TP in the initial rainfall runoff could reach 50.46% and 51.77%, the reduction rates of SS in the initial rainfall runoff are 46.51% and 56.91%, and the reduction rates of NH_3-N in the initial rainfall runoff could reach 33.45% and 18.04% when the amount of split-flow are 3 mm. Therefore, it is an economical alternative to use the initial disposal as a primary treatment method for road rainfall reuse system.

4 CONCLUSIONS

(1) The initial runoff pollution was serious, and the highest concentrations of SS, COD, NH_3-N and TP in the initial runoff were 410 mg/L, 282.4 mg/L, 11.18 mg/L and 1.2 mg/L. With the increase of rainfall duration, the concentrations of pollutants gradually reduced, and finally stabilized. In addition, the decreasing trend of the concentrations of SS, COD, NH_3-N and TP were related to the number of sunny days, rainfall and rainfall intensity.

(2) According to the pollution load rate calculation, when the initial rainfall split-flow was designed to be 3 mm, more than 60% of the pollutant load on rainfall road runoff could be removed, which was the goal of Sponge City Construction in China.

(3) Aiming at the engineering simulation of the university, the results of the engineering simulation on pavement showed that the reduction rates of COD, TP, SS, NH_3-N on the pavement rainfall could reach 48.15%, 51.77%, 56.91% and 33.45% when the amount of initial split-flow was 3 mm. It indicated that the initial rainfall disposal could be used as primary treatment of pavement rainfall reuse system in rainfall utilization.

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