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Stormwater Quality Characteristics and Reuse Analysis of Different Underlying Surfaces at Wanzhou North Station

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ABSTRACT

In response to the water shortage in Wanzhou North Station (WNS), the authors investigated the stormwater quality characteristics with different underlying surfaces of WNS and carried out stormwater reuse analysis in conjunction with the InfoWorks ICM model. The results show that during heavy, torrential, and moderate rainfall, the road stormwater runoff has the highest concentrations of pollutants, with an average EMC (event mean concentration) value of 206 mg/L for COD. For the square runoff, the average EMC values of COD, SS, TN, and TP are 108 mg/L, 395 mg/L, 2.113 mg/L, and 0.128 mg/L, in comparison, the average EMC values of the corresponding indexes for the roof runoff are 65 mg/L, 212 mg/L, 1.449 mg/L, and 0.086 mg/L, respectively, demonstrating their potential for reuse. The R^2 (coefficient of determination) of SS and COD in both roof and square runoff is greater than 0.85, with a good correlation, indicating that SS removal is the key to stormwater purification. InfoWorks ICM analysis shows that the recyclable volume of rainwater from WNS in 2018 is 29,410 m^3, accounting for 61.8% of the total annual rainfall. This study is expected to provide an ideal reference for the stormwater management of public buildings in mountainous areas.

1. Introduction

Rapid urbanization has destroyed the original hydrological characteristics of the city, not only making the problem of surface pollution more prominent but also wasting a lot of rainwater resources [1-4]. Rainwater resource utilization is an effective way to relieve the pressure on water supply and drainage and improve the water environment, which can bring good environmental benefits and is one of the essential elements of sponge city construction [5-7]. A large number of studies have been carried out in China on stormwater utilization. Ouyang et al. [8] analyzed the rela-

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tionship between stormwater runoff pollutants from different underlying surfaces and the preceding dry period, rainfall amount, and rainfall intensity, and proposed that controlling initial rainwater and sweeping the subsurface can reduce runoff pollution. Yuan et al. [9] found that the correlation between SS and COD, TP, and ammonia nitrogen in rainwater runoff from different underlying surfaces in Xi'an is strong, and SS is a key factor affecting runoff water quality. In addition, there are cases in Beijing and Nanjing where roof and road surface rainwater has been used for greening and watering in public building areas and road washing after filtering treatment [10,11]. In general, current research on rainfall-runoff focuses on pollution control and treatment processes, with less emphasis on stormwater utilization demands and recyclable stormwater volumes.

As a pilot project of the sponge city program in Chongqing, the rainwater utilization rate goal in the Wanzhou District is ≥ 3%. Currently, rainwater resource utilization has become one of the priorities of energy-saving management in large public buildings [12]. Promoting a healthy water cycle and strengthening the construction of ecological sponge watersheds is the demand for water management, while rainwater resource utilization is also an important measure to strengthen the natural water cycle and social water cycle [13,14]. In this study, the rainfall amount and the rainfall duration of WNS are monitored in real-time to study the water quality characteristics of stormwater runoff from different underlying surfaces and the correlation between each pollutant, and the amount of recyclable rainwater is analyzed using the InfoWorks ICM model, to provide a reference for rainwater harvesting and utilization in large public buildings of mountainous cities.

2. Materials and Methods

2.1 Rainfall Monitoring

The rainfall amount in WNS was monitored in real-time by using the telemetry rain gauge. In this paper, three rainfall events (heavy rain, torrential rain, and moderate rain) within the regional catchment were selected for water quality testing, considering that the greater the rainfall, the greater the number of potential rainwater resources, and the rainfall characteristic parameters are shown in Table 1.

2.2 Sample Collection and Analysis

The stormwater water quality of three kinds of underlying surfaces such as roads, squares, and roofs was tested. Sampling points were located at the rainwater inspection well on the left rear side of the station, the square storm sewer, and the road rainwater inlet.

Water sample collection method: sampling every 5 min within the first 30 min after rainfall production flow, every 10 min within 30-60 min, and every 30 min after 60 min. The testing index includes SS, COD, TN, ammonia nitrogen, nitrate nitrogen, TP, etc. The analysis method refers to the "Water and Wastewater Monitoring Analysis Method (Fourth Edition)".

2.3 Data Processing and Analysis

Event mean concentration (EMC): The average concentration of pollutants discharged during the entire course of runoff from a field rainfall event is used because the runoff pollutant concentration is constantly changing during the rainfall process, i.e., EMC to characterize the pollution load of stormwater runoff [15]. Its calculation formula is:

$$EMC = \frac{\sum C_t Q_t \Delta t}{\sum Q_t \Delta t} = \frac{\sum C_t V t}{\sum V t}$$

Among them: Δt—the time interval of sampling collection (min); Vt—the amount of runoff rainwater in t period (m³); Ct—concentration of runoff pollutants in t period (mg/L).

3. Results and Discussion

3.1 Change Law of Rainwater Runoff Water Quality

3.1.1 Road

As can be seen from Figure 1, in the three rainfall events, the concentration of major pollutants in road stormwater runoff rose to a high level at the beginning of the flow production, gradually decreased after 20 min and leveled off after 60 min. The SS concentration ranges from 10 mg/L to 2912 mg/L and EMC average value of 838 mg/L, COD concentration ranges from 7 mg/L to 570 mg/L, and EMC average value of 206 mg/L in the three rainfall events. This is due to the frequent vehicular and

Table 1. Characteristics of rainfall events.

Time	Rainfall amount/ (mm)	Rainfall duration /(min)	Maximum rainfall intensity/ (mm/min)	Average rainfall intensity/ (mm/min)	Preceding dry period/d
2018/07/30	41.5	255	0.8	0.16	17
2018/09/20	63.0	610	1.6	0.10	12
2019/10/07	18.0	225	0.3	0.08	8

pedestrian activities on the road, producing pollutants such as road material abrasives, garbage, and oil; on the other hand, the dry period before rain for both heavy and torrential rainfall events is more than 10 d, with a large accumulation of pollutants, resulting in poor road stormwater runoff water quality with high SS and COD content. Hou et al. [16] found that the water quality of runoff from Beijing ring road trunk roads exceeded the V standard of the Environmental Quality Standards for Surface Water (GB3838-2002), and the pollutants mainly came from the abrasion of wheels and road materials as well as atmospheric deposition and vehicle exhaust, which was consistent with this study.

TN ranges from 0.690 mg/L to 6.877 mg/L and EMC average value of 3.271 mg/L in the three rainfall events, which exceeds the surface water V standard, while ammonia nitrogen and nitrate nitrogen range from 0.050 mg/L to 1.192 mg/L and 0.230 mg/L to 2.683 mg/L, respectively, which means that organic nitrogen has a high proportion in TN, indicating a certain degree of organic pollution of rainwater. The peak pollutant concentrations of heavy rain, torrential rain, and moderate rain occurred at 15 min, 10 min, and 15 min, respectively, and the concentrations of COD, SS, and TN in the runoff at the beginning of the storm were significantly higher than those of heavy rain and moderate rain, which indicated that the runoff flushed the subsurface more strongly during the storm [17,18], making the peak pollution concentration forward. This shows that the road stormwater runoff is subjected to a higher level of pollution and is not suitable for recycling.

3.1.2 Square

From Figure 2, it can be seen that during the heavy rainfall and torrential rainfall events, the COD of the rainfall-runoff from the square reached the peak of 255 and 355 mg/L at 15 min and 10 min after the flow production, respectively, and the SS also reached the highest values of 801 and 1578 mg/L at this time; in the medium rain event, the COD reached the peak of 34 mg/L at 10 min after the flow production, and the SS reached the peak of 123 mg/L at 20 min after the flow production, it indicates that the organic matter mostly exists in the suspended state, which may be influenced by the construction dust on the right side of the square. There was a rise and then a decrease in TN and TP, which eventually leveled off, with the average EMC value of 2.113 mg/L and 0.128 mg/L respectively, and TN exceeded the surface water category V standard. The pollution level of the square rainfall runoff was significantly reduced after 20 min, the water samples were observed to be clearer when sampling and their EMC mean values of TN, ammonia nitrogen, nitrate nitrogen,

TP, COD, and SS were reduced to 1.272, 0.188, 0.754, 0.098, 76, and 215 mg/L, while only COD exceeded the surface water category V standard. The main pollutants of the square rainwater runoff are COD and SS, and the quality of the collected rainwater can be greatly improved by the initial rainwater abandonment and ground sweeping.
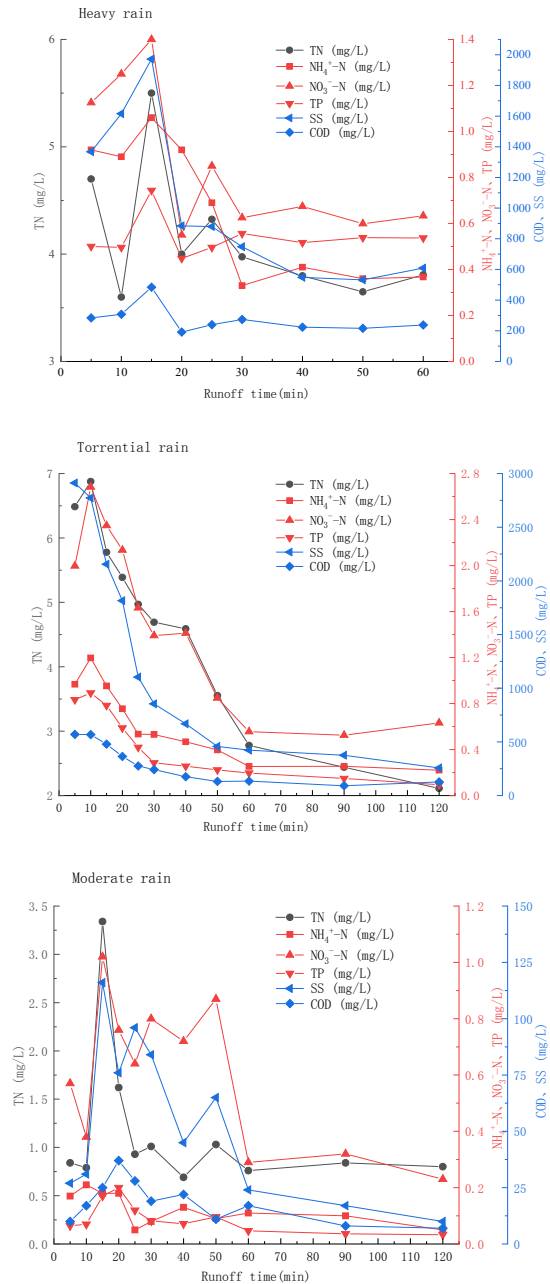

Figure 1. Variation curve of road stormwater runoff water quality.

It is not difficult to see that the water quality of the rainwater runoff in the moderate rain was significantly better than in the previous two rainfalls, which shows that with the gradual improvement of the construction of the WNS Sponge City, the runoff pollution in the Tianzi Lake

watershed has been alleviated. Considering the correlation between SS and COD, the concentration of pollutants can be further reduced by precipitation or clarification [18], so that the square rainwater has good reuse potential.
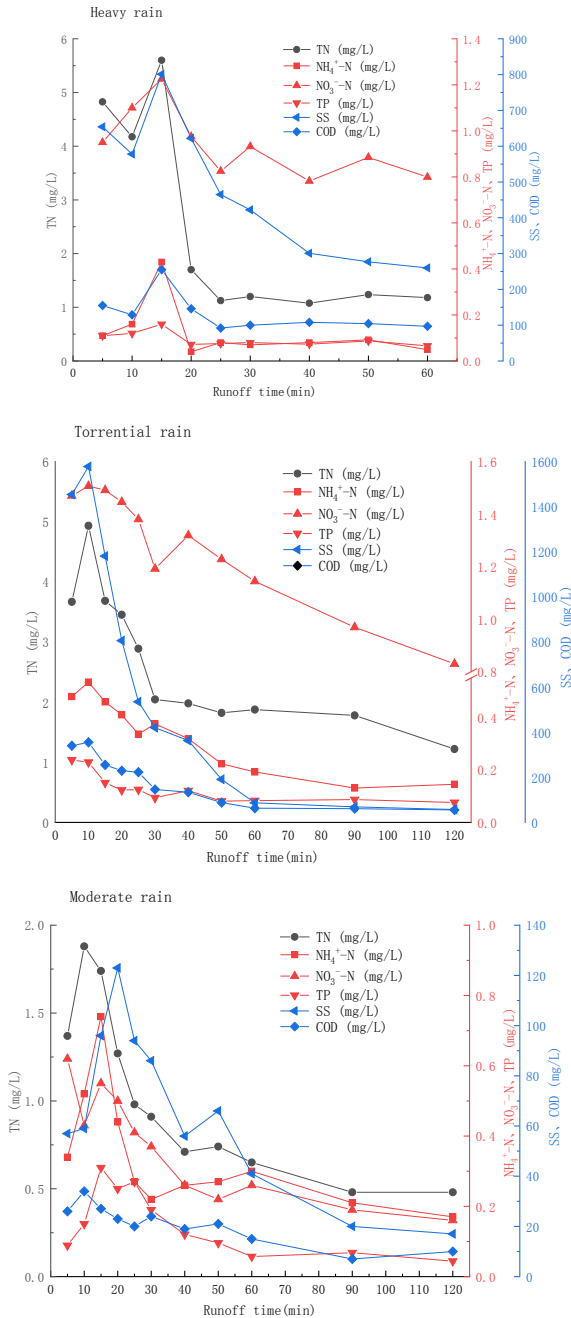

Figure 2. Variation curve of square stormwater runoff water quality.

3.1.3 Roof

In general, roof pollutants mainly come from atmospheric deposition and roofing materials [19,20], and the roof of the station house in this study is made of metal, which

has minimal effect on runoff water quality. The mean EMC values of TN, ammonia nitrogen, nitrate nitrogen, TP, COD, and SS in roof rainwater runoff were 1.449, 0.201, 0.626, 0.086, 65, and 212 mg/L, respectively, which were significantly better than the road and square runoff water quality, and the main pollution indicators were still COD and SS.

From Figure 3, it can be seen that the TN and nitrate nitrogen concentrations fluctuated greatly in the three rainfall events, with the peak TN in heavy rain and heavy rain appearing at the beginning of the flow production, and the peak TN in medium rain appearing at 20 min of flow production. The peaks of TN, ammonia nitrogen, and nitrate nitrogen caused by heavy rain were higher than those of torrential rain and medium rain, while the peaks of SS, COD, and TP were lower than those of torrential rain but higher than those of medium rain, which may be due to the longer number of sunny days in the early part of heavy rain and the higher accumulation of NOx in the air. Yuan et al. [9] calculated the contribution of atmospheric drenching and subsurface scouring to pollutants and found that atmospheric drenching was the main source of rainwater ammonia nitrogen, and subsurface scouring was the main source of TP, SS, and COD, which indicated that the higher COD and SS were caused by stormwater flushing. With the gradual improvement of the supporting projects of WNS, the construction dust will gradually disappear. Comparing the runoff water quality of three rainfall events, it can be seen that the roof runoff water quality is gradually becoming better, and it can be predicted that soon the roof runoff water quality will be significantly better than the current stage, with good potential for recycling.

3.2 Analysis of Initial Scour Effect

The subsequent discussion focuses on stormwater from the square and the roof, as the reuse value of road stormwater was found to be low in combination with the process change characteristics of runoff water quality. In this paper, we evaluate the scour effect according to Geiger [21], and if the difference between the slope of the M(V) curve and the diagonal slope is greater than 0.2, the initial scour is considered to have occurred. During heavy and torrential rainfall events, the cumulative pollution load curves of TP, TN, ammonia nitrogen, and SS in the rainfall-runoff from the square and the roof are above the diagonal line, as shown in Figure 4 and Figure 5, indicating that a certain degree of initial scouring occurred, but the scouring effect of nitrate nitrogen was not obvious. The first flushing of TN in torrential rainfall events was more significant than that in heavy rainfall events, mainly because the dry

period before the rain was longer and the nitrogen content was higher due to atmospheric washing and surface scouring effects. The concentrations of ammonia and nitrate nitrogen in the rainfall runoff from the square were low, but the initial TN flushing effect was obvious, and it can be presumed that the initial flushing object was mainly organic nitrogen.
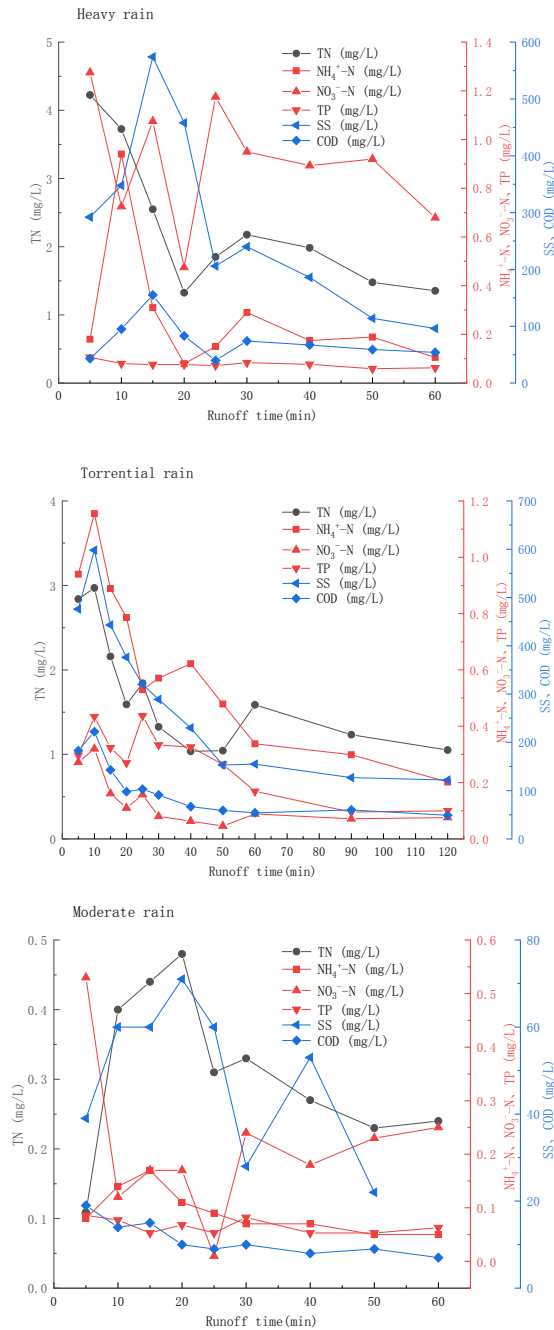

Figure 3. Variation curve of roof stormwater runoff water quality.

The first flushing of rainwater on the roof was not obvious, probably because, in the rainfall process, the slope of the roof is conducive to the collection of rainwater, but the metal roof is not easy to attach particles. The square, however, has a larger catchment area, is more significantly affected by human activities, has a larger accumulation of pollutants [22,23], and is prone to first flushing. The runoff water quality is influenced by the frequency of ground sweeping, human activities, rainfall amount, rainfall intensity, and the dry period before rain [24], which makes the rainfall-runoff scour curves of different underlying surfaces both similar and complex.
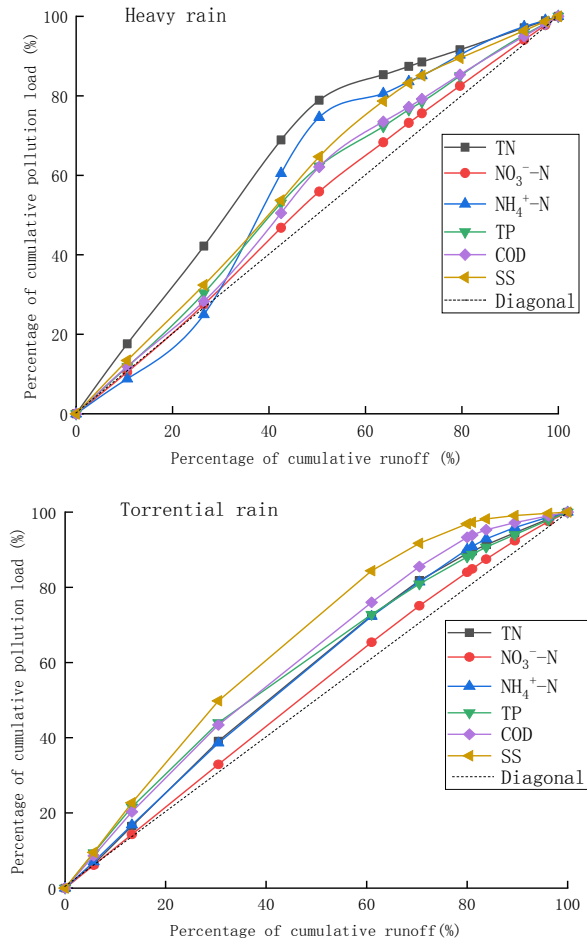

Figure 4. Cumulative distribution curves of square runoff pollution load.

3.3 Analysis of Runoff Pollutants

Identifying the source of pollutants is essential for runoff pollution reduction and stormwater resource utilization, so the source of pollutants was analyzed in conjunction with the coefficient of determination R^2 (see Table 2) between the indicators [25]. There was a good correlation between COD, ammonia nitrogen, nitrate nitrogen, TN, TP, and SS of the square runoff at the significance 0.01 level, and the R^2 values were all greater than 0.6, which can be presumed that COD and ammonia nitrogen of the
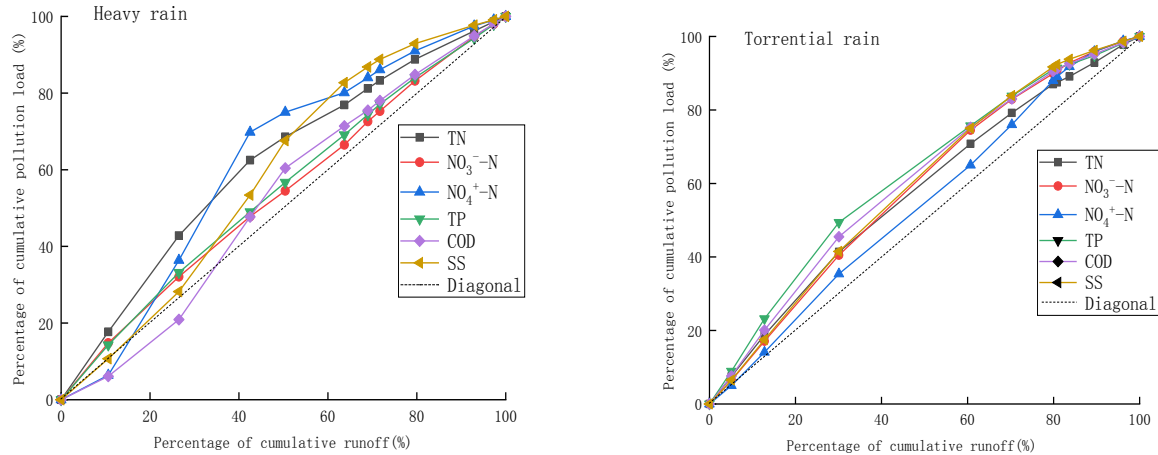
Figure 5. Cumulative distribution curves of roof runoff pollution load.

square were endowed in the particulate state and accumulated on the ground [23]; the R^2 values of SS and COD, ammonia nitrogen, nitrate nitrogen, TN, and TP were 0.95, 0.75, 0.70, 0.71, and 0.89, indicating that the effective removal of SS can effectively improve stormwater quality.

COD of roof runoff was well correlated with TP and SS, TP with SS at the significance 0.01 level, and their R^2 values were 0.87, 0.86, and 0.67, respectively, indicating that SS is homologous with COD and TP, which is consistent with the results obtained by Zhao et al. [22] studying the characteristics of pollutant changes in rainfall-runoff; while ammonia nitrogen was correlated with SS and TP, nitrate nitrogen with SS and COD. TN and TP have no significant correlation, and TN and SS have a weak correlation at the significance 0.05 level, which is signifi-

cantly different from the correlation between the pollutant indicators of square runoff, probably because in the process of runoff generation and pooling, nitrogen is mainly dissolved in the rainwater in the dissolved state, and the amount attached to suspended matter is less.

3.4 Prediction of Recoverable Rainwater Amount

InfoWorks ICM was used to simulate the rainfall and its runoff process in WNS. The fixed PR Model was used for the flow production model of the roof and square, and the fixed runoff coefficient was taken as 0.9. Horton Infiltration Model was used for the flow production model of the green area. The SWMM model was used for the confluence model of each sub-bedding surface, and the system of St. Venant equations was used for the pipe cal-

Table 2. Linear correlation coefficients between the pollution of different underlying surfaces of rainfall runoff.

Underlying surface	Contaminant	Determination coefficients R^2					
		COD	NH_4^+-N	TN	TP	SS	NO_3^--N
Square	COD	1					
	NH_4^+-N	0.85**	1				
	TN	0.75**	0.67**	1			
	TP	0.96**	0.88**	0.76**	1		
	SS	0.95**	0.75**	0.71**	0.89**	1	
	NO_3^--N	0.79**	0.92**	0.62**	0.77**	0.70**	1
Roof	COD	1					
	NH_4^+-N	0.38	1				
	TN	0.38	0.52*	1			
	TP	0.87**	0.23	0.43	1		
	SS	0.86**	0.38	0.51*	0.67**	1	
	NO_3^--N	0.17	0.20	0.53*	0.41**	0.81	1

Note: *at the 0.05 level (two-tailed), ** at the 0.01 level (two-tailed), the correlation is significant; the coefficient of determination R^2 = the square of the correlation coefficient R.

culation.

The measured data of the September 20 rainstorm event were organized into the module format specified by ICM, with the rainfall calendar time set to 4 h and the initial rainfall volume abandoned at 5 mm, and the simulation yielded a late cumulative runoff volume of 2142 m^3. This means that the recoverable rainfall volume for this rainfall event is 2142 m^3, which is 73.4% of the total rainfall volume. The analysis showed that the accumulated rainfall days of WNS in 2018 were 125 d and the total rainfall amount was 1028 mm, and continuous rainfall simulation was performed by inputting the measured 5 min rainfall data of that year, which resulted in the recoverable rainfall amount of 29410 m^3, accounting for 61.8% of the total rainfall amount of that year. It can be seen that WNS can recycle a large amount of rainwater, because the main pollution index of the roof and square rainwater runoff for SS and COD, can be combined with the site topography conditions set rain gardens, bio-retention facilities, permeable paving, storage ponds and other green facilities to detain and purify stormwater, to achieve the dual effect of runoff pollution reduction and stormwater recycling.

3.5 Benefits Analysis

Stormwater reuse is conducive to relieving water supply pressure, reducing pollution of receiving water bodies, and improving the ecological environment. According to the idea of local consumption, rainwater can be considered for watering the square, roads, and green areas of WNS [26]. The water demand is measured according to the area of the square, green space, and road, combined with relevant standards, see Table 3 for details. InfoWorks ICM analysis shows that the recoverable water is 29,410 m^3/a, accounting for 40.4% of the miscellaneous water demand of WNS. If the water price is 4 yuan/m^3, the annual water cost can be saved by 117,600 yuan.

Table 3. Forecast of miscellaneous water demand of WNS.

Use	Water quota L/(m^2·d)	Service area/(m^2)	Annual water consumption/(m^3)
Square	2.5	31300	28560
Afforestation	2.0	3724	2718
Road	2.5	45435	41458
footing	6.5	80459	72736

Rainwater utilization is one of the important tasks of urban stormwater management [27], which can promote the effect of total annual runoff control, enhance social awareness of water conservation, make people feel the environmental enhancement brought by sponge city construction, and is of great significance to enhance the well-being of the public, with significant social benefits.

4. Conclusions

(1) The average EMC values of SS, COD, TN, and TP in road stormwater runoff are 1,228, 293, 4.425, and 0.496 mg/L, respectively. While the road runoff is not suitable for harvesting and reuse, the water quality of square and roof runoff is considerably better, with contaminants mainly in the form of SS and COD (i.e., 581 and 159 mg/L for square runoff, 293 and 92 mg/L for roof runoff). The TN and TP of rainwater runoff in the latter period are close to the regulatory standards for water reuse, which means less treatment is required and therefore a lower overall cost for rainwater utilization.

(2) The TN and TP of the square and roof runoff have different degrees of initial scouring, and the determination coefficients R^2 of SS and COD are all greater than 0.85, which shows a strong correlation, indicating that the reduction of suspended solids is critical for rainwater reuse.

(3) Using InfoWorks ICM simulation, it is concluded that the annual recyclable rainfall of WNS is 29,410 m^3, accounting for 40.4% of its miscellaneous water demand. Rainwater harvesting and reuse can alleviate flooding in urban areas and reduce water consumption. As one of the emerging practices for water conservation, it is expected to play an important role in sustainable urban planning and construction.

Conflict of Interest

There is no conflict of interest.

Funding

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