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Article

Monitoring and studying rainfall runoff pollution from urban impervious surfaces

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Abstract: Urban impervious surface rainfall runoff pollution is a significant component of non-point source pollution, with pollutants accumulating on these surfaces during dry periods being the primary source of contaminants in rainfall runoff. Using the first ten rainfall events of 2015 as a case study, impervious surfaces such as the roofs of teaching buildings, campus roads, and nearby main traffic roads within the university campus in southeastern Beijing were selected for field sampling and analysis of natural rainfall and rainfall runoff pollution. The findings indicate that the initial rainfall runoff pollution following winter is severe, with water quality falling below Class V. Subsequently, the pollution levels decrease; however, the severity of water pollution varies at different sampling locations. Notably, ammonia nitrogen concentrations are higher near building toilet exhaust outlets, and the presence of pervious surface facilities can mitigate runoff pollution. Based on the analysis and research findings, several recommendations for controlling and managing urban rainfall runoff pollution are proposed.

Keywords: urban impervious surface; runoff pollution; rainfall; pollution control

Urban rainfall runoff pollution refers to the water pollution caused by rainwater and its runoff scouring the urban surface (mainly impervious surface) under rainfall conditions, so that soluble or solid pollutants flow into the receiving water body from non-specific places [1]. With the continuous strengthening and improvement of point source pollution control in China, and the rapid development of urbanization in China, urban impervious surface rainfall runoff pollution as a non-point source pollution has been paid more and more attention, and has gradually become the focus and hot spot of experts and scholars.

On the basis of referring to the research status of rainfall runoff pollution at home and abroad, this paper collected and detected rainfall runoff samples in the campus of Beijing University of technology, counted and analyzed the detection results, found some laws, and provided some references for the control and treatment of rainfall runoff pollution.

1. Comparison of domestic and foreign studies

Since the 1980s, the United States, Europe and other developed countries have carried out large-scale investigation and Research on the characteristics and causes of urban rainfall runoff pollution, and developed some models for management and research, including SWMM, storm, etc. On the basis of the research, the "best management practices (BMPs)" scheme for urban rainfall runoff pollution control is also proposed, which has been widely used [2].

The research in China was later than that in the developed countries in Europe and America. In the late 1980s, the research was carried out in Beijing, Suzhou, Tianjin, Yunnan and other places. Shi provides a new research method for quantitative calculation of urban rainfall runoff pollution load [3]; Wang et al. focused on the initial scouring [4]; Dong et al. Further identified and verified the parameters of SWMM model in urban impervious surface runoff simulation [5]; Chen et al. believe that the accumulation of urban surface pollutants and the process of rainfall scouring are the dynamic processes of sedimentation, suspension, re sedimentation and suspension, respectively. They also put forward that the dry days before rain (adwp) is an important influencing factor of the model [6]. However, these studies are mainly related to international trends [7,8].

The research on urban impervious surface rainfall runoff pollution should be based on a large number of measured data. This paper analyzes and studies 650 samples of the first 10 rainfall events in 2015 on the campus of Beijing University of technology.

2. Experimental scheme

2.1. Selection of sampling location

In this study, the campus area of Beijing University of Technology is selected as the study area. According to the surface characteristics of the study area, six sampling points are selected, which are located in the West Campus of Beijing University of Technology and the adjacent Xidawang Road. The specific settings are as follows: a) Sampling point is arranged in the square of the west campus to pour cement; b) No. 1 sampling point is arranged on the cement road in the west campus; c) No. 1 sampling point is arranged on the non motorized lane of Xidawang Road adjacent to the west campus, which is asphalt pavement; d) No. 1 sampling point is arranged next to the rainwater grate of the motor vehicle lane of Xidawang Road, which is an asphalt pavement; e) No. 1 sampling point is arranged at the rainwater inlet on the roof of the West Building of China Construction Engineering Group, and the roof is paved with impervious bricks; f) No. 1 sampling point is the natural rainfall sampling point to study the water quality of natural rainfall. The layout of rainfall runoff sampling points is shown in **Figure 1**.

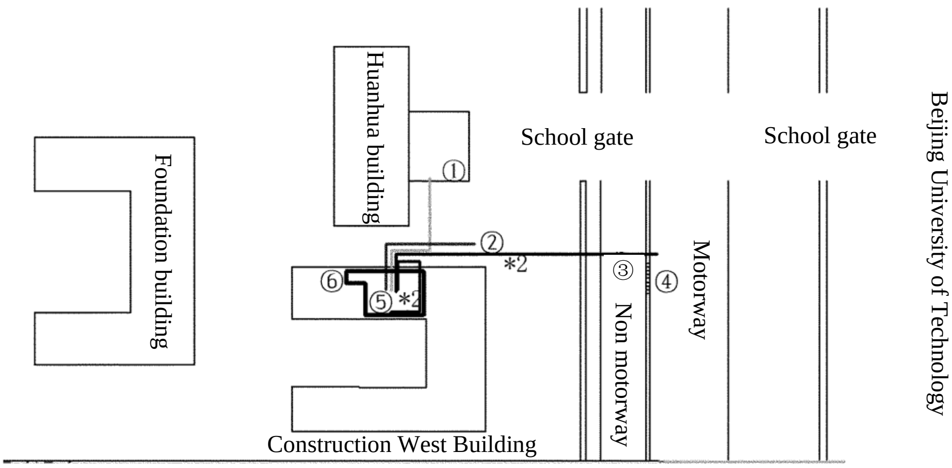

Figure 1. Layout of sampling site.

Pervious bricks are paved beside the roads in the campus. Rainwater runoff generally flows through the pervious bricks, and then is discharged into the adjacent rainwater grate by the school gate.

2.2. Collection of rainfall runoff samples

Rainfall runoff samples are collected by the rainfall runoff collection device self-made by Beijing Key Laboratory of water quality science and water environment restoration, Beijing University of technology [9]. The console is shown in **Figure 2**.

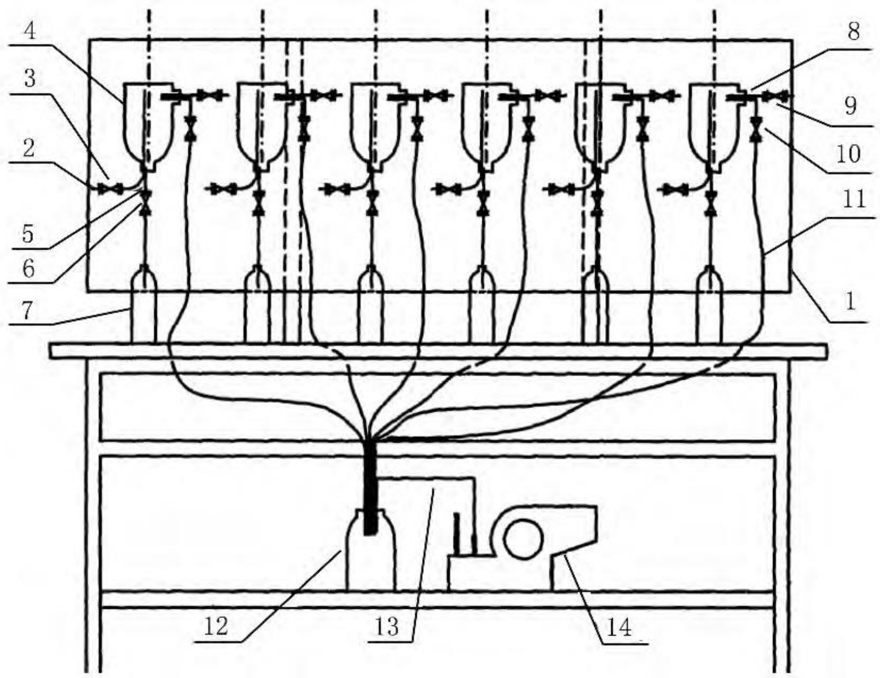

Figure 2. Schematic diagram of indoor operation console of sampling device.

1. Sampling platform; 2. Outdoor rainwater collection and introduction conduit; 3. Rainwater inlet valve; 4. Indoor rainwater collection bottle; 5. Connect the rainwater sample bottle conduit; 6. Rainwater drainage valve; 7. Rainwater sample bottle; 8. Ventilation duct of indoor rainwater collection bottle; 9. Vent valve; 10. Vacuum valve; 11. Indoor rainwater collection bottle vacuum pipe; 12. Vacuum buffer bottle; 13. Connect the vacuum pump pipe; 14. Vacuum pump.

The samples are collected at the time when the rainfall is about to produce runoff. The sampling frequency is determined according to the rainfall intensity. Generally, the sampling interval is 5~15 min. When the rainfall lasts for a long time, the sampling interval is 0.5, 1 h, etc. After sampling, the samples shall be sent to the laboratory for test, and the test shall be completed within 24 h.

2.3. Supporting instruments

The laboratory is also equipped with JDZ02-1 tipping bucket rain gauge to accurately record the rainfall process.

3. Data statistics and analysis

3.1. Rainfall records

Rainfall process records shall be accurate. The rainfall in each period provides the basis for the calculation of each index pollutant. See **Table 1** for the recorded statistical results of rainfall process.

Table 1. Statistical results of rainfall process mm.

Test date	Time	Water depth	Test date	Time	Water depth
2015.03.31	19:20	0	2015.05.01	16:25	0
	20:00	0.20		16:55	1.27
	20:30	0.48		17:10	2.23
	20:50	1.27		17:40	3.50
	21:10	2.07		18:10	4.14
	21:30	3.03		18:30	4.62
	21:50	3.90		19:00	5.25
	22:10	4.38		20:50	5.73
	23:00	4.62		21:30	6.05

3.2. Analysis results of rainfall runoff pollution

Water quality index is an important parameter to evaluate water quality, and a relatively complete index system has been formed. This paper adopts the method of monitoring and analysis methods for water and wastewater (Fourth Edition) to detect some conventional indicators [10]. With reference to surface water environmental quality standards and reclaimed water quality standards, the proposed water quality indicators include TOC, TN, COD, TP, ammonia nitrogen, etc.

Taking the first rainfall runoff sample collected as an example, the water quality test results are shown in **Table 2**.

Table 2. Change process of rainwater runoff concentration on 31 March 2015 mg/L.

Place	Number	Time	TOC	TN	COD	TP	Ammonia nitrogen
Hospital Road	1	21:00	186.60	43.11	382.30	4.77	22.98
	2	21:04	51.57	40.14	73.74	0.95	21.15
	3	21:16	40.90	36.25	72.24	0.65	21.00
	4	21:26	40.27	38.25	81.27	0.48	20.38
	5	21:54	27.33	23.20	63.11	0.28	13.55
	6	22:23	26.22	22.28	60.20	0.26	11.50
	7	22:52	25.83	21.86	60.11	0.25	11.50
Courtyard square	1	21:16	375.00	42.82	560.20	6.25	29.40
	2	21:28	98.40	35.43	133.70	0.37	20.10
	3	21:43	71.45	28.55	87.00	0.27	16.43
	4	22:01	44.63	19.58	70.80	0.29	12.10
	5	22:28	38.72	19.57	65.80	0.24	11.20
	6	22:50	37.22	19.36	64.10	0.23	11.20
Main traffic road	1	21:22	307.90	34.88	1285.80	9.20	18.40
	2	21:27	72.52	30.90	190.32	0.88	17.75
	3	21:43	43.32	26.40	85.78	0.54	17.75

	4	22:05	44.01	25.22	80.20	0.40	13.55
	5	22:21	43.05	25.08	77.70	0.34	13.68
	6	22:50	42.53	24.33	74.71	0.31	13.15
Campus gate	1	21:07	505.50	45.39	1132.00	10.85	27.45
	2	21:16	70.15	38.58	109.80	0.55	18.28
	3	21:26	54.42	36.53	93.31	0.33	17.23
	4	21:57	41.04	25.08	77.72	0.29	14.33
	5	22:23	36.63	21.71	76.69	0.27	12.50
	6	23:02	34.30	21.22	72.24	0.20	11.20
Courtyard roof	1	21:00	45.45	22.20	61.17	0.35	21.63
	2	21:21	25.61	20.89	46.65	0.12	19.23
	3	21:53	23.76	18.33	39.43	0.09	14.23
	4	22:33	21.75	18.22	34.36	0.09	14.23
Natural rainfall			21.73	17.79	33.11	0.07	20.50

3.3. Data statistics and analysis

(1) Before the first rainfall in 2015, due to the concentration of pollutants in the air in the whole winter without precipitation, compared with some index values in the environmental quality standard for surface water (see **Table 3**), the water quality of the collected natural rainfall is inferior to the class V standard for surface water, and the water quality is very poor.

Table 3. Comparison between measured value of natural rainfall and standard limit value mg/L.

Project	COD	Ammonia nitrogen	TP	TN
Class I	15.00	0.15	0.02	0.20
Class Π	15.00	0.50	0.10	0.50
Class Ш	20.00	1.00	0.20	1.00
Class IV	30.00	1.50	0.30	1.50
Class V	40.00	2.00	0.40	2.00
Natural rainfall	33.11	20.50	0.07	17.79

With the arrival of rainy season, the accumulation time of pollutants in the air becomes shorter, rainfall leaching is frequent, and the water quality pollution of natural rainfall is reduced. See **Table 4** for some test results.

Table 4. Test results of some natural rainfall rainwater quality g/L.

Date	TOC	TN	COD	TP	Ammonia nitrogen
2015.03.31	21.73	17.79	33.11	0.07	20.5
2015.04.02	10.32	7.23	15.62	0.03	3
2015.05.01	12.51	8.02	15.5	0.05	5.05
2015.05.10	15.6	8.64	14	0.03	1.07
2015.06.04	14.16	8.17	16.4	0.06	2.16

2015.06.26	12.45	7.83	14.52	0.06	1.86
2015.07.01	10.2	7.35	16.8	0.06	2.49

(2) The sources of pollutants and external interference at different sampling points are different, as shown in **Table 5**.

Table 5. Influencing factors of pollutant sources on different underlying surfaces.

Place	**Atmospheric dust fall**	**Human activity**	**Vehicle**	**Sanitation cleaning**	**Other**
Roof	✓				Impact of toilet exhaust passage
Campus square	✓	✓		✓	
School Road	✓	✓	✓	✓	
Main traffic road	✓		✓	✓	Impact of road construction
Traffic auxiliary road	✓	✓		✓	Impact of road construction

(3) Before the first rainfall in 2015, the particulate matter in the air accumulated a large number of pollutants in the ground area after a long winter without precipitation. At the same time, the concentration of pollutant indicators in the initial rainfall runoff was generally too large due to the untimely sanitation cleaning. The COD concentration in the main traffic road and school gate even exceeded 1100 mg/L. The concentration value of each index pollutant in the rainfall runoff after entering the rainy season is less than that of the first rainfall runoff.

4) The first rainfall in Beijing in 2015 occurred at 19:00 on 31 March from 20, the earliest rainfall runoff occurs at 21:00, from the school roof and the school road. Due to the large number of drought days before rainfall, the initial loss of rainfall is large, and the runoff occurs late. Then, runoff occurs within 1 h in each rainfall in the rainy season. Because there is a certain slope on the roof of the campus building, the runoff is formed earliest.

(5) It can be seen from **Table 6** that the initial scouring effect of the first rainfall is obvious, and the initial scouring amount of rainfall runoff accounts for about 80% of the total scouring amount. However, the initial scouring rate of each rainfall entering the rainy season is 40%~50%.

The calculation formula of scouring effect at the initial stage of rainfall is: pollutant concentration of each index × Rainfall in corresponding period ÷ area = mass per unit area of pollutants; accumulation of mass per unit area of pollutants in each period = mass per unit area of pollutants scoured in the whole process of rainfall. The scouring effect is the ratio of initial scouring amount to total scouring amount.

Take the TOC of the school road as an example to calculate: initial scouring amount = $186 \times 1.7 \div 1000 \times 1 \times 1000 \div 1 = 316$ mg/m^2, total scouring amount = $(186 \times 1.7 + 51.5 \times 0.2 + 40.9 \times 0.4 + 40.2 \times 0.55 + 27.3 \times 1.1 + 26.2 \times 0.5 + 25.8 \times 0.15) \div 1000 \times 1 \times 1000 \div 1 = 411.97\ \mathrm{mg/m^2}$.

Initial scour rate = 316/411.97 = 0.77 = 77%.

(6) The rainwater runoff in the campus shall be collected and discharged into the nearest rainwater grate through the gate of the campus. During the collection process, it shall flow through the permeable brick floor. After calculation, the pollution of each pollutant is: (campus road + campus square + campus roof) > campus gate. For

example, the emission per unit area of TOC (412 + 971) in **Table 6** is > 1165 mg/m^2, indicating that the pervious brick laying can reduce the pollutants in the runoff.

Table 6. Initial scouring monitoring results.

	Hospital Road			**Courtyard square**			**Main traffic road**			**Campus gate**		
	Initial scouring amount/(mg·m^{-2})	**Initial scouring rate/%**	**Total scour/(mg·m^{-2})**	**Initial scouring amount/(mg·m^{-2})**	**Initial scouring rate/%**	**Total scour/(mg·m^{-2})**	**Initial scouring amount/(mg·m^{-2})**	**Initial scouring rate/%**	**Total scour/(mg·m^{-2})**	**Initial scouring amount/(mg·m^{-2})**	**Initial scouring rate/%**	**Total scour/(mg·m^{-2})**
TOC	316	412	77	863	971	89	875	954	92	1035	1165	89
COD	650	860	76	1288	1456	88	3662	3815	96	2321	2542	91
TP	8.1	9.6	84	14.4	15.1	95	26.2	27.6	95	22.1	22.9	96

(7) The pollutant concentration is different at different sampling points. The roof pollution of the teaching building in the school is the lightest. The pollutants come from atmospheric sedimentation and are almost free from external interference, so the concentration of each pollutant is small; in addition to atmospheric sedimentation, the school gate and traffic roads are also subject to external human and traffic interference, which is complex and changeable and difficult to control, so the concentration of pollutants is large; on impervious surfaces such as school roads and school squares, the pollutants are affected by atmospheric sedimentation, but the human factors and traffic factors are less than those of traffic roads. The pollution degree is more serious than that of roofs and slightly less than that of traffic roads.

(8) Ammonia nitrogen is one of the important pollution factors in rainfall runoff pollution. In the 12th Five Year Plan adopted at the Fifth Plenary Session of the 17th Central Committee of the Communist Party of China held in October 2010, it was clearly proposed to take ammonia nitrogen as a binding indicator for the discharge of major water pollutants in the country. In this study, it is found through statistical calculation that the ammonia nitrogen in runoff pollutants mainly comes from natural rainfall, but the average concentration of ammonia nitrogen in natural rainfall is smaller than that in previous rainfall, and larger than that in later rainfall, so there is an abnormal situation. It is found that the ammonia nitrogen in natural rainfall mainly comes from the exhaust gas discharged from the toilet outlet of the building. In the later experiment, a relatively independent toilet exhaust port was selected, and the ammonia nitrogen was detected during the natural rainfall on 1 May and 10, 2015, with the exhaust port as the center and the sampling points 0, 5 and 10 m away from the exhaust port. The results are shown in **Tables 7** and **8**. It can be seen from **Tables 7** and **8** that the concentration of ammonia nitrogen in the rainwater of natural rainfall decreases with the increase of the distance from the toilet exhaust port and the extension of rainfall time.

Table 7. Change of ammonia nitrogen concentration on 1 May 2015.

Distance from toilet exhaust outlet/m	Time	Ammonia nitrogen/(mg·L^{-1})	Distance from toilet exhaust outlet/m	Time	Ammonia nitrogen/(mg·L^{-1})
0	17:35	5.94	0	21:00	306
5		5.68	5		290
10		5.47	10		259

Table 8. Change of ammonia nitrogen concentration on 10 May 2015.

Distance from toilet exhaust outlet/m	Time	Ammonia nitrogen/(mg·L^{-1})	Distance from toilet exhaust outlet/m	Time	Ammonia nitrogen/(mg·L^{-1})
0	13:00	6.626	0	15:50	1646
5		5.525	5		1.174
10		5.053	10		0965
0	14:00	2.747	0	18:20	1069
5		2.694	5		0860
10		2.537	10		0650

4. Conclusion

Based on the field experiment and data analysis, the conclusions are as follows:

(1) The water quality of the first natural rainfall in the rainy season is poor. After entering the rainy season, the water quality pollution of the natural rainfall is reduced.

(2) The sources of pollutants and external interference at different sampling points are different, and the pollution degree at different sampling points is different.

(3) In the rainfall event, the concentration of pollutants in the initial rainfall runoff is generally larger, and the initial scouring effect of rainfall runoff pollution is obvious.

(4) Due to different materials and slopes of impervious surfaces, different drought days before rainfall and other reasons, the time of rainfall runoff is different.

(5) Pervious brick laying can reduce pollutants in runoff.

(6) In the rainwater quality of natural rainfall, as a pollutant, the concentration of ammonia nitrogen decreases with the increase of the distance from the building toilet exhaust outlet, and decreases with the extension of rainfall time.

5. Suggestions and prospects

(1) The collection of rainfall runoff samples needs a lot of manpower and material resources, and the research and development of automatic collection is imperative.

(2) At present, the monitoring of rainwater quality in China is weak and data is lacking. In the future, we should strengthen the monitoring of rainwater quality to provide sufficient and reliable data for scientific research.

(3) Attention should be paid to the research and development of high-strength permeable paving facilities to give full play to their role in reducing pollutants in rainwater runoff.

(4) Scientifically control the exhaust gas discharged from the toilet exhaust outlet of buildings, reduce the pollution of ammonia, hydrogen sulfide, methane, etc. To the atmosphere, so as to achieve the purpose of reducing the pollution of rainfall runoff.

(5) Improve the awareness of environmental protection, ensure the quality of sanitation, and prohibit the direct discharge of ground pollutants into the adjacent rainwater grate. In particular, the impervious surface shall be cleaned before rainfall to reduce the pollution of urban impervious surface runoff.

(6) Natural zeolites NH_4^+ have good selective adsorption performance for ammonia removal, even in the presence of interfering cations such as water hardness (Ca^{2+}, Mg^{2+}) [11]. China is rich in zeolite resources. Zeolite can be used to treat ammonia nitrogen in rainfall runoff, that is, a zeolite filter layer is added under the rainwater grate at the inlet to make full use of the adsorption performance of zeolite for ammonia nitrogen and reduce the concentration of ammonia nitrogen in rainfall runoff. If the rainfall runoff finally flows into the sewage treatment plant, it can reduce the nitrogen removal pressure of the sewage treatment plant; if the rainfall runoff is finally discharged into the river, the eutrophication of the water body can be reduced.

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