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A Source Pollution Control Measure Based on Spatial-Temporal Distribution Characteristic of the Runoff Pollutants at Urban Pavement Sites

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Received: 31 August 2018; Accepted: 20 September 2018; Published: 2 October 2018

Featured Application: It is recommended that the design of source pollution control measures be based on the spatial-temporal distribution characteristics of pavement runoff pollutants.

Abstract: The concentrations of pollutants in urban pavement runoff are normally higher than those in other urban surface runoff, which causes serious problems in protecting the environment of receiving water and soils. The purpose of this study was to propose a source pollution control measure based on the spatial-temporal distribution characteristics of the runoff pollutants at urban pavement sites. Therefore, samples from pavement runoff were collected and tested for analyzing the spatial-temporal distribution characteristics. Then, infiltration tests were conducted on selected purification materials to evaluate their purification ability to the simulated pavement runoff. Results indicated that heavy metals Zn and Pb were at high concentrations near the intersection, the reason being the frequent braking of vehicles at this site. The level of suspended solids was far higher than the limitation in the standard near the site where massive human activities occurred. Besides, the cumulative amounts of all kinds of pollutants tended to be stable with the extension of rainfall duration. The logarithmic function was found to fit the experimental data well. Finally, the pavement runoff was categorized into different situations. The combinations of purification materials were recommended and integrated into a source control measure for the treatments of different pollution situations, which made the most use of each purification material and ensured the high elimination efficiency of different pollutants.

Keywords: pavement engineering; runoff pollutants; spatial-temporal distribution; source control measures; purification materials

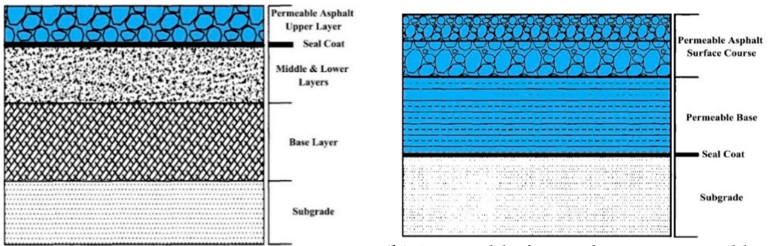
1. Introduction

In the context of stormwater management in the urban area, different practices, including low impact development (LID), sustainable urban drainage systems (SUDS), water sensitive urban design (WSUD) and best management practices (BMPs) have been developed in succession over recent decades [1–3]. The definition of BMPs has since become a more universal term describing best practices related to general pollution prevention [4,5]. Positively, the point source pollutions, such as domestic sewage, industrial emissions and so on have been minimized to a satisfied level with the building of both non-structural and structural control attributes [6]. However, non-point source pollutions caused mainly by the rapid increase of impermeable urban pavement and traffic vehicles are becoming more and more serious [7–9]. As the principal part of non-point source pollutions, pavement runoff pollution has attracted extensive attention from engineers and agencies of pavement engineering. Field investigations carried out in different countries indicated that the pollutants in pavement runoff exceeded the limitation in the local standards to a great extent [10–12]. How to control the pavement runoff pollution more efficiently tended to be a significant problem most engineers pay close attention to. However, most existing investigations focused on the development of pollution control measures (PCMs) and purification materials, ignoring the influence of spatial-temporal distribution characteristics.

Actually, the characteristics of pavement runoff pollutants is of great importance to the design and layout of PCMs. Early in 1995, Barrett reported the main sources of pavement runoff pollutants, including traffic vehicles, atmospheric sedimentation, construction, maintenance and other human activities. The typical characteristics of pavement runoff pollutants are influenced by traffic volume, rainfall parameters, pavement types, existing status of pollutants, ambient environment and climatic features [13,14]. The concept "first flush" is also mentioned in publications, which illuminates that high concentration pollutants exist in the first flush of rainfall events [15,16]. About 60% total suspended solid (TSS) was found in the 30% first flush rainfall [17]. Investigations showed that there are evident correlations between the concentrations of different pollutants. The heavy metal Zn is positively correlated to dissolved organic carbon (DOC) while Pb, Fe and Al are positively correlated to TSS [18]. The nutrients TN and TP are related to TSS, too [19]. All these findings provide a good way to remove pollutants in pavement runoff by filtrating DOC and TSS. As to other factors, conclusions were drawn by Mayer and Winston that the chemical pollutants and biological toxicity of highway runoff with heavy traffic volume are far higher than those with light and medium traffic volume [20], and that the amount of TSS in open graded friction course (OGFC) runoff is less than that in impermeable pavement runoff, meaning the outstanding performance of permeable pavements in pollutant removal [19].

PCMs such as source management, detention ponds, frequent street cleaning, wetlands, sedimentation basins, and percolation treatments are designed for different situations [13]. Gill monitored the removal efficiency of a constructed wetland planted with *Phragmites australis* and *Typha latifolia* to highway pavement runoff, and found that the removal rate of heavy metals Cd, Cu, Pb and Zn is up to 95%, 88%, 86% and 95%, respectively [21]. To make the most of the absorptivity of environmental mineral materials and the decomposition of microorganisms, the combination of zeolite, rock wool and microorganisms is used in the rainwater purification system, which shows good removal ability for COD, SS, NH_3-N, TP and TN [22].

Environmental mineral materials were also employed by Hilliges in a three-stage treatment system for highly polluted urban road runoff [23]. In recent years, permeable asphalt pavement, widely paved in the Netherlands, has been accepted broadly as an effective way to reduce the peak of rainfall runoff and detain particle pollutants [24,25]. It has higher air voids ranging from 18% to 25% than traditional hot mix asphalt (HMA), which makes the rainwater infiltrate into pavement structure layers and drain away laterally along the seal coat [26]. The typical structures of permeable asphalt pavement are shown in Figure 1. Other PCMs are also reported in the literature, such as wet bio-filtration and dry detention ponds [27].



(**a**) Permeable only for upper layer (**b**) Permeable for surface course and base

Figure 1. Permeable asphalt pavement structure.

Currently, however, few reports are found about the PCMs based on the spatial-temporal distribution characteristics of pavement runoff pollutants. Generally, studies mainly focus on the composition, concentration and first flush phenomenon of pavement runoff pollutants. The purpose of PCMs is to remove the amount of pollutants as much as possible. Spatial distribution characteristic of pollutants may be different at each section along the road, due to the surrounding environment and human activities. This means that the design and layout of PCMs should be made by the specific distribution characteristics of pollutants. Taking Figure 2 as an example, the concentration levels of A and B are high in Sections 4–6 while that of C is high in Sections 8–10. According to this characteristic, environmental mineral materials with different removal rate for pollutants A, B and C could be placed at corresponding sections.

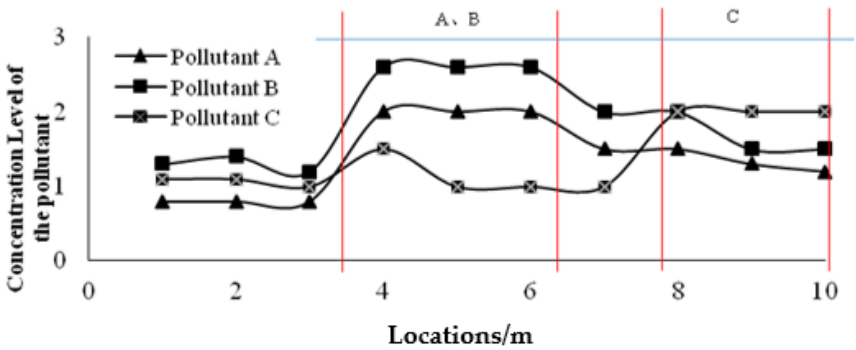


Figure 2. Hypothetical distribution characteristics of pollutants along a road.

To have this goal realized, the spatial-temporal distribution characteristic of pollutants are presented in this paper by sampling and analyzing the pavement runoff at different spots along the road. Then, pavement runoff simulations were prepared in the laboratory and used in the infiltration test to obtain the removal rate of six purification materials on different pollutants. Combined with the actual pollution situations of RRS, the combinations of purification materials were recommended and integrated into a source control measure. This paper proposes a specific technology for pavement runoff pollution control based on the actual pollution situations and the removal rate of different purification materials.

In future applications, PCMs containing different purification materials selected for both their removal rate of different pollutants and the actual pollution situations will be placed along the road for on-site treatment, especially where heavily polluted pavement runoff occurs. As an artificial barrier material provides a reliable elimination of pollutants, the infiltration of treated pavement runoff without endangering soil or even groundwater pollution is possible.

2. Materials and Methods

2.1. Study Site and Sampling

The Runyang Road South (RRS) is the connection line between a highway and a municipal road in Yangzhou, China. It has high traffic volume and is close to the laboratory. Four spots were selected as the target sites for sampling, as shown in Figure 3. The first one is at the intersection. The third one is near the gate of Yangtze campus. The other two are along the road.

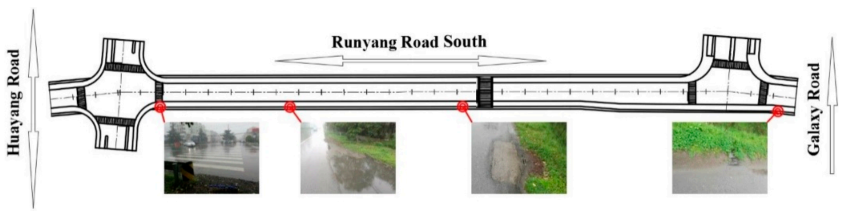


Figure 3. Sampling sites of pavement runoff.

Limited by the nature of pavement runoff, manual sampling was adopted in this study. Syringes were used to collect the pavement runoff which was then stored in clean sampling bottles. The entire sampling process started from the formation of runoff and lasted about 1 h. The time points of sampling were set as 1, 3, 5, 8, 10, 15, 20, 30, 45, and 60 min.

From October 2012 to April 2016, samplings were carried out during ten rainfall events in RRS. In this study, a typical pavement runoff collected on 3 April 2016 was chosen as the samples to analyze the spatial-temporal distribution characteristics. The rainfall and sampling conditions are shown in Table 1.

Table 1. Rainfall and sampling conditions.

Date of Sampling	Precipitation (mm)	Duration of Rainfall (min)	Duration of Runoff (min)	Duration of Sampling (min)
3 April 2016	14.7	153	143~148	60

2.2. Sample Analysis and Simulated Pavement Runoff

Pavement runoff samples were promptly sent to the laboratory for water quality analysis after sampling. The analysis indexes included SS, COD, TN, TP, Zn, and Pb. The monitoring methods are shown in Table 2.

Table 2. Analysis methods of different pollutants.

Items	Methods	Referenced Standards
SS	Gravimetric method	GB/T11901-89
COD	Potassium dichromate method	GB/T11914-89
TN	Alkaline potassium persulfate digestion UV spectrophotometric method	HJ 636-2012
TP	Ammonium molybdate spectrophotometric method	GB 11893-89
Pb	Atomic absorption spectrophotometry method	GB 7475-87
Zn	Atomic absorption spectrophotometry method	GB 7475-87

A large volume of pavement runoff was needed in the experiment. However, it was inconvenient and difficult to collect sufficient pavement runoff from the field. Therefore, a pavement runoff simulation was prepared as per the actual concentration of the pollutants by using the chemical reagents listed in Table 3.

Table 3. Chemical reagents for simulated pavement runoff.

Indexes	SS	COD	TN	TP	Zn	Pb
Reagent	Roadside dust	$C_6H_{12}O_6$	NH_4Cl	KH_2PO_4	$Zn(NO_3)_2$	$Pb(NO_3)_2$

2.3. Purification Materials

To make the best use of waste materials, fine sand, zeolite, slag, ceramsite, diatomite and scoria were selected as the purification materials and subjected to simulated pavement runoff.

Zeolite is a kind of microporous aluminosilicate mineral discovered by a Swedish mineralogist, Cronstedt, now widely used as ion-exchange beds in domestic and commercial water purification, softening, and other applications. Slag is the by-product of blast furnace ironmaking. Ground granulated slag is often used in combination with Portland cement as part of a blended cement. Ceramsite is a kind of light aggregate produced by foam technology in a rotary kiln. The honeycomb structure inside endues the ceramsite with satisfactory absorptivity. Diatomite is a typical biomineral with porous structure and large specific surface area [28], which provides an ideal carrier for heavy metal ions. Scoria is a highly vesicular, dark colored volcanic rock. It has low density because of its numerous macroscopic ellipsoidal vesicles. Their macroscopic morphologies are presented in Figure 4.

(**a**) Zeolite (**b**) Slag (**c**) Ceramsite (**d**) Diatomite (**e**) Scoria

Figure 4. Purification materials.

2.4. Purification Experiment

The device shown in Figure 5 was designed and used in the infiltration experiment to test the removal ability of different purification materials to the pollutants listed in Table 2.

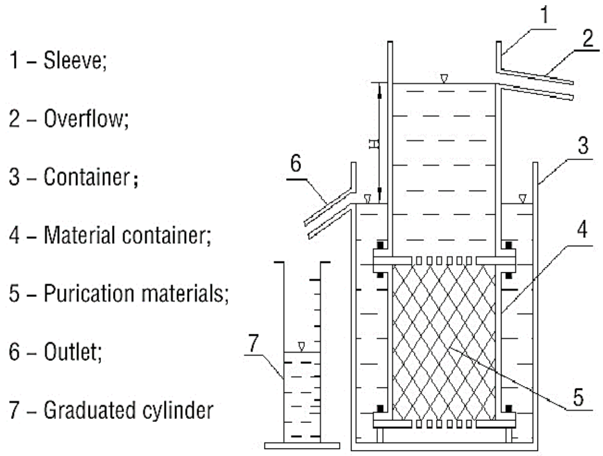


Figure 5. Device for the purification experiment.

The simulated pavement runoff was pumped up into the sleeve and then infiltrated through the purification materials into the container. The effluent was collected 2 min after the beginning of the experiment by using a graduated cylinder and immediately sent to the laboratory for water quality analysis. The entire experiment was carried out under constant head.

3. Results and Discussion

3.1. Spatial-Temporal Distribution Characteristics Analysis

The results of water quality analysis are listed in Table 4. It was evident that the concentration of each pollutant far exceeded the limitation of Grade V required in the Standard of Environmental Quality for Surface Water [29]. Especially, the concentrations of COD and SS were at high levels with the duration of the rainfall at all four sites, which indicated that organic and particle pollution were serious in the entire area. The detailed spatial-temporal distribution characteristics are discussed below.

Table 4. Sample analysis results.

Sites	Rainfall Duration (min)	TN (mg/L)	TP (mg/L)	COD (mg/L)	Zn (mg/L)	Pb (mg/L)	SS (mg/L)
Site 1	0	12.333	2.019	616	7.670	1.175	496
	3	11.994	2.014	564	6.510	1.370	711
	5	10.317	1.720	560	5.395	1.645	674
	10	10.217	1.593	636	4.705	1.240	700
	15	9.189	1.303	664	4.390	0.595	633
	20	9.146	1.061	692	3.735	2.065	490
	30	7.095	0.806	584	3.375	1.910	316
	40	5.038	0.912	524	2.995	0.920	139
	50	5.020	0.819	716	2.640	0.520	72
	60	5.021	0.906	704	2.245	0.730	104
Site 2	0	5.132	1.403	540	3.370	0.540	403
	3	4.183	1.017	380	2.870	0.550	585
	5	4.095	1.010	712	2.385	0.545	370
	10	3.048	1.002	772	1.925	0.360	217
	15	3.013	0.934	744	1.255	0.320	105
	20	3.037	0.709	632	1.195	0.295	50
	30	2.018	0.708	492	0.665	0.355	67
	40	2.031	0.710	776	0.230	0.380	130
	50	1.048	0.805	764	0.215	0.380	120
	60	1.007	0.716	700	0.260	0.795	71
Site 3	0	10.561	4.034	552	5.105	0.775	1018
	3	9.313	3.827	400	4.515	0.620	853
	5	8.327	3.523	696	3.870	0.610	1437
	10	6.178	3.040	396	3.180	0.570	858
	15	6.136	2.607	408	2.005	0.335	661
	20	5.327	2.019	568	1.935	0.390	663
	30	5.154	1.710	804	1.655	0.295	309
	40	5.063	1.311	576	1.310	0.245	184
	50	4.106	1.017	872	0.895	0.315	215
	60	2.022	1.015	664	0.740	0.730	11
Site 4	0	6.304	2.129	624	2.060	0.540	750
	3	6.135	1.718	492	1.705	0.380	389
	5	5.110	1.813	700	1.055	0.250	380
	10	4.110	1.508	752	1.000	0.235	251
	15	4.028	1.004	800	0.800	0.240	225
	20	3.125	1.013	796	0.615	0.340	220
	30	3.072	0.863	760	0.265	0.230	238
	40	3.153	0.906	604	0.120	0.465	204
	50	3.033	1.008	460	0.075	0.275	172
	60	1.008	0.729	692	0.050	0.485	145
Limitation (Grade V)		≤ 2	≤ 0.2	≤ 40	≤ 2	≤ 0.1	<30

3.1.1. Spatial Distribution Characteristics of Pavement Runoff Pollutants

Box charts of different pollutants are plotted in Figure 6.

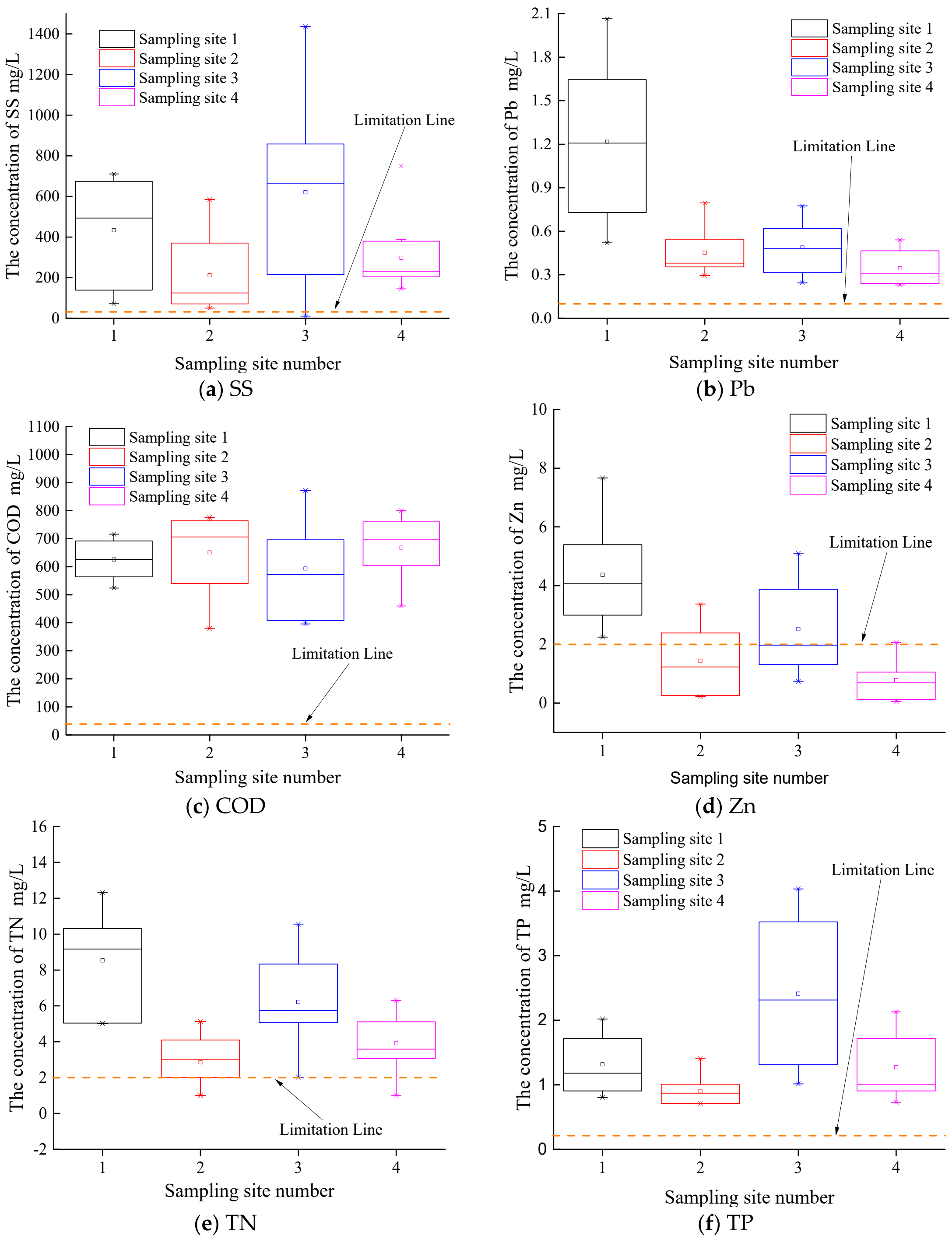


Figure 6. Box charts of different pollutants.

The pollutants SS, Zn and Pb showed very clear spatial distribution characteristics. In Figure 6a, the concentrations of SS at Sites 3 and 1 were much higher than those at the other two sites. These two sites were near the intersection and the west gate of Yangtze Campus, respectively. Large amounts of particle dusts or other suspended pollutants brought by vehicles and pedestrians passing by may be the reason for this characteristic. SS is a typical quality index for surface water, the maximum concentration of which was up to 48 times more than the limitation value. Particles of suspended matter are usually visible to human eyes, unstable in water and easy to be removed by porous adsorptive materials. As to the heavy metals Pb and Zn (Figure 6b,d), high concentrations existed in the pavement runoff near the intersection (Site 1). This is due to exhaust emission and frequent braking of vehicles at such sites.

However, COD showed the same concentration level at all four sites, which indicated that there were many organic pollutants in this area. In Figure 6e,f, the spatial distributions of TN and TP were similar to that of SS because dissolved pollutants attach to particles.

3.1.2. Temporal Distribution Characteristics of Pavement Runoff Pollutants

Ten samples collected in Site 1 are shown in Figure 7. Visually, the turbidity highly related to the concentration of SS declining with the extension of rainfall duration.

Figure 7. Samples of pavement runoff.

To better understand the temporal distribution characteristics of pavement runoff pollutants, different elementary functions were adopted to fit the water quality analysis data.

The natural logarithmic function, shown in Formula (1), was found to fit the cumulative concentration of different pollutants quite well. In the formula, C_c represents the cumulative concentration of different pollutants. t represents the time point of sampling. a and b are the coefficient and constant, respectively. The fitting results for different pollutants at four sites are listed in Table 5.

$$C_c = a \cdot \ln(t) + b \tag{1}$$

Table 5. The fitting results for different pollutants at four sites.

Items		Fitting Results		R^2	Items		Fitting Results		R^2
		a	b				a	b	
SS	Site 1	1057.20	435.25	0.95	Zn	Site 1	9.4321	5.9133	0.99
	Site 2	404.07	588.65	0.95		Site 2	2.8734	4.0392	0.94
	Site 3	1424.6	1054.2	0.94		Site 3	5.2462	5.3276	0.98
	Site 4	578.43	636.31	0.99		Site 4	1.4852	2.5092	0.92
Pb	Site 1	3.0108	−0.0563	0.96	TN	Site 1	19.384	7.7671	0.98
	Site 2	0.9459	0.1947	0.97		Site 2	6.305	4.1668	0.98
	Site 3	0.9987	0.5371	0.98		Site 3	13.679	7.9176	0.99
	Site 4	0.7169	0.1681	0.95		Site 4	8.6679	4.7657	0.99
COD	Site 1	1464.2	−162.43	0.96	TP	Site 1	2.8676	1.5756	0.99
	Site 2	1572.3	−381.71	0.95		Site 2	1.9779	0.7055	0.98
	Site 3	1382.71	−321.74	0.93		Site 3	5.3052	3.5971	0.98
	Site 4	1628.7	−246.82	0.95		Site 4	2.7355	1.5902	0.99

Taking SS as an example, the correlation curve between time and concentration of SS is plotted in Figure 8.

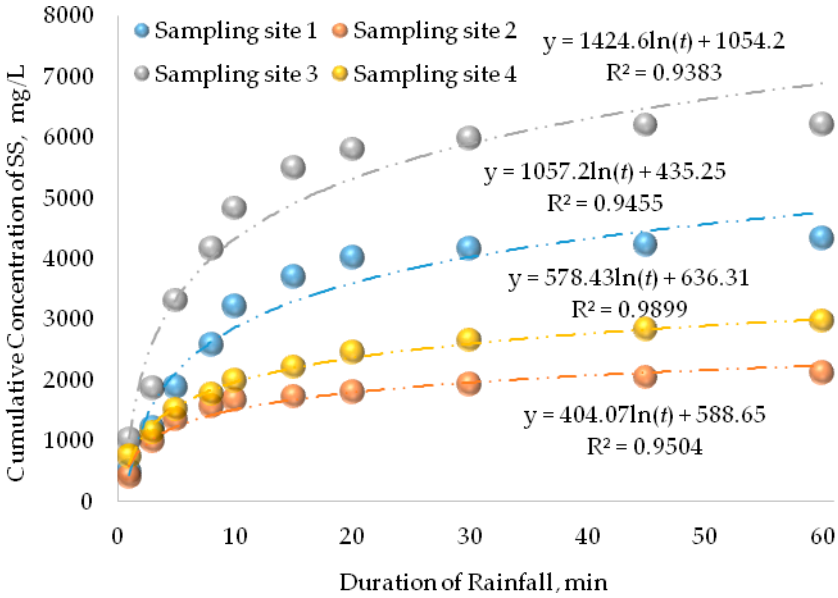


Figure 8. The correlation curve between time and concentration of SS.

The increase of the natural logarithmic function proves the continuous input of pollutants during the entire rainfall event. Additionally, the curve increases sharply at the initial stage and then tends to gradually stabilize. This property is consistent with the first flush effect of rainfall events. The cumulative concentration reached a high level in a very short time and then ascended slowly due to the slight input of pollutants. Although the average concentrations of all pollutants are greater than the limitation in the standard, the real-time concentrations become lower and lower, up to a moment when the concentration was lower than the limitation value. This moment, t_c, is defined as the critical time point, for pollution control of pavement runoff. Taking TN at Site 2 as an example, the concentration, 1.048 mg/L, meets the requirement of the standard 50 min after the formation of pavement runoff, which means that the critical time point is between 40 and 50 min. It is not necessary to process the TN in the pavement runoff after this point. However, the concentrations of most pollutants analyzed in this study were not lower than the limitation value within 60 min.

3.2. A Source Control Measure Based on the Optimal Combinations of Purification Materials

To develop effective control measures for treating pavement runoff pollution, four pollution situations were determined based on the analysis above. The first situation, denoted as A, contains high concentration SS and small amounts of other pollutants. The second situation, denoted as B, contains high concentration heavy metals Pb and Zn. Pavement runoff with high concentration dissolved pollutants TN and TP belongs to the third situation, C. If the concentrations of all pollutants are at approximate level, it is viewed as the last situation, D. The removal rates, calculated by Formula (2), of six purification materials on different pollutants are listed in Table 6.

$$(|C_{2\min} - C_0|/C_0) \times 100\% \quad (2)$$

In Formula (2), C_0 is the initial concentration and $C_{2\min}$ is the concentration 2 min after the beginning of infiltration experiment.

Because of differences in pore structure, pore size and mineral composition the six materials have different removal rates for different pollutants. Each pollutant corresponds to an optimal purification material. Since it is impossible to use one purification material that has a better effect in treating pavement runoff [30], combinations of purification materials applicable for different pollution situations would be of great significance in processing the pavement runoff more efficiently.

Table 6. Results of the infiltration experiment.

Purification Materials	Removal Rates (%)					
	SS	COD	TN	TP	Zn	Pb
Fine sand	95.1	34.7	8.6	43.1 *	36.4	47.3
Zeolite	96.4	48.5 *	45.7	40.3 *	55.9 *	56.0
Slag	97.3 *	45.2 *	45.3	20.8	36.4	10.8
Ceramsite	94.6	40.1	27.4	20.8	73.4 *	78.7 *
Diatomite	88.9	42.3	50.6 *	31.9	21.9	26.0
Scoria	99.5 *	30.4	56.9 *	15.3	34.0	84.7 *

Note: In each column, the top two removal rates are marked with *.

The combination including two purification materials was taken as an example in this paper. In each column of Table 6, the top two removal rates are marked with asterisk. For the pollution situation containing only one kind of high concentration pollutant, the purification materials corresponding to the top two removal rates would be the best for this pollution situation. Therefore, the best combination for A (SS) includes scoria and slag. For the pollution situation containing two or more high concentration pollutants, the combination should be determined by considering mutual complementation of purification materials. Thus, for B (Pb and Zn), zeolite and ceramsite were selected. Finally, the optimal combinations of purification materials applicable for different pollution situations are listed in Table 7.

Table 7. Optimal combinations of purification materials applicable for different pollution situations.

Pollution Situations	A	B	C	D
Combination	Slag + Scoria	Zeolite + Ceramsite	Zeolite + Diatomite	Zeolite + Scoria

Based on the RRS runoff pollution characteristics, the advantages and disadvantages of various control measures, we referred to the three-stage treatment system [23] to integrate different purification materials into a source control measure to process the pavement runoff. The measure was designed as a portable device shown in Figure 9. To ensure the growth of plants, the container cover was made of glass.

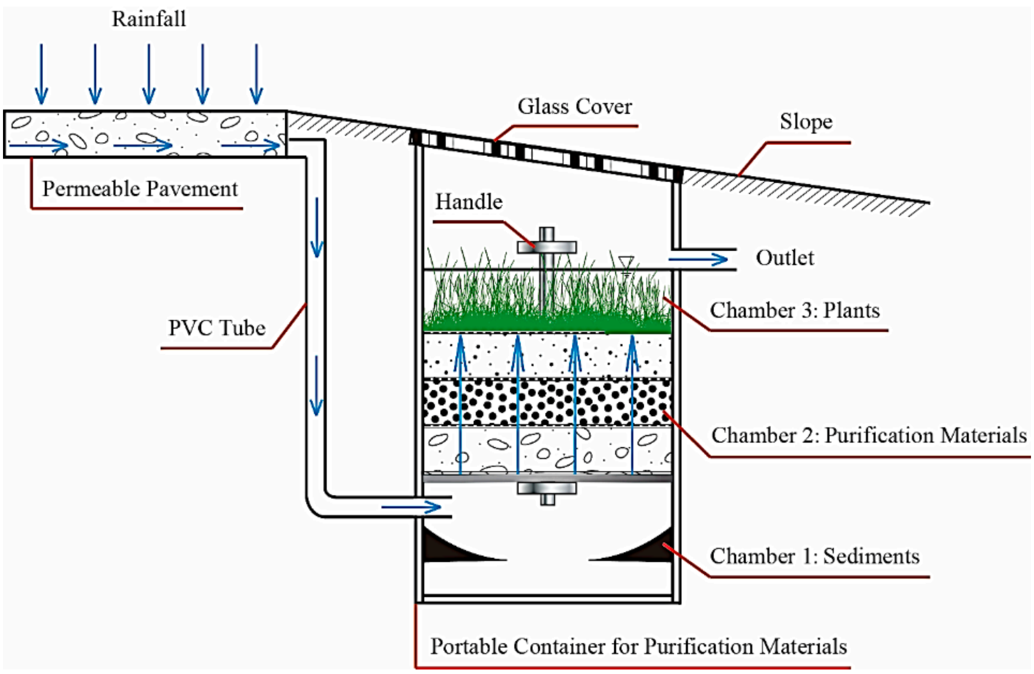


Figure 9. A Portable Device of Pollution Control Measures.

The runoff went through the permeable pavement or other media, was collected by PVC tube and flowed into the processing chambers. Bigger particles sank in Chamber 1 while smaller particles and dissolved pollutants continued flowing through Chamber 2 and 3. The flow from the bottom up extended the time that pavement runoff went through the purification materials chamber, which provided full contact between pollutants and materials and helped to improve the removal rate. The purification materials and plants absorbed and detained most of the pollutants. Chambers 2 and 3 were placed on a removable plate with a handle. This made the replacement of old or saturated materials more convenient. Finally, the processed runoff was drained out directly to nearby water bodies or stored into recycling units for reuse in municipal irrigation.

4. Conclusions

The spatial-temporal distribution characteristics of the runoff pollutants at urban pavement sites were investigated by analyzing the water quality indexes of pavement runoff samples collected from RRS. The following conclusions can be drawn:

(1) The concentrations of Pb and Zn at the intersection were much higher than those at other sections of the road. The level of suspended solids far exceeded the limitation near the site where frequent human activities occurred. The spatial distributions of dissolved pollutants were similar to that of SS because of their high attachment to particles.

(2) For all pollutants, the cumulative concentration reached a high level in a very short time and then ascended slowly. They were finally stable with the extension of rainfall duration. This feature was consistent with the property of the natural logarithmic function.

(3) Six materials showed different removal rates for different pollutants. Based on the spatial-temporal distribution characteristics of pavement runoff pollutants, combinations of purification materials applicable for different pollution situations were recommended.

(4) Different purification materials were integrated into a source control measure for treating pavement runoff with high pollution potential.

(5) Depending on area locations, surrounding environment and rainfall events, the spatial and temporal distribution characteristics of pavement runoff were different. Only on the premise of understanding the actual pollution situations can engineers integrate different purification materials in the PCMs to make the removal of pollutants more effective and efficient.

Author Contributions: Data curation, C.K. and P.M.; Formal analysis, C.K.; Investigation, C.K., P.M., H.B., L.S. and Z.W.; Methodology, A.K. and P.X.; Project administration, A.K. and P.X.; Validation, Z.W.; Visualization, C.K.; Writing—original draft, C.K.; Writing—review and editing, A.K. and P.X.

Funding: This research was funded by the Natural Science Foundation Committee of China, grant number 51578481 and 51578480, and the Research and Innovation Plans for Graduates, grant number kyzz15_0363. The APC was funded by the Natural Science Foundation Committee of China".

Acknowledgments: The authors would like to acknowledge the financial support of the Natural Science Foundation Committee of China (51578481 and 51578480) and the Research and Innovation Plans for Graduates (kyzz15_0363). We would also like to thank the technical support from the Testing Center of Yangzhou University and the Centre for Pavement and Transportation Technology at the University of Waterloo in Canada.

Conflicts of Interest: The authors declare no conflict of interest. The sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

1. Finnemore, E.J.; Lynard, W.G. Management and control technology for urban stormwater pollution. *J. Water Pollut. Control Fed.* **1982**, *54*, 1099–1111. [CrossRef]
2. Van Roon, M. Low impact urban design and development: Catchment-based structure planning to optimize ecological outcomes. *Urban Water J.* **2011**, *8*, 293–308. [CrossRef]

3. Fletcher, T.D.; Shuster, W.; Hunt, W.F.; Ashley, R.; Butler, D.; Arthur, S.; Trowsdale, S.; Barraud, S.; Semadeni-Davies, A.; Bertrand-Krajewski, J.-L.; et al. SUDS, LID, BMPs, WSUD and more—The evolution and application of terminology surrounding urban drainage. *Urban Water J.* **2015**, *12*, 525–542. [CrossRef]
4. Environmental Protection Agency. *National Pollutant Discharge Elimination System (NPDES) Definitions*; 40 C.F.R. § 122.2 (2011a); United States Environmental Protection Agency: Washington, DC, USA, 2011.
5. Environmental Protection Agency. *National Pollutant Discharge Elimination System (NPDES) Establishing Limitations, Standards, and Other Permit Conditions*; 40 C.F.R. §122.4 (2011b); United States Environmental Protection Agency: Washington, DC, USA, 2011.
6. Ghassemi, A. *Handbook of Pollution Control and Waste Minimization*, 1st ed.; Marcel Dekker Inc.: New York, NY, USA, 2002; pp. 389–392.
7. Bannerman, R.T.; Owens, D.W.; Dodds, R.B.; Hornewer, N.J. Sources of pollutants in Wisconsin stormwater. *Water Sci. Technol.* **1993**, *28*, 241–259. [CrossRef]
8. McCarthy, D.T.; Hathaway, J.M.; Hunt, W.F.; Deletic, A. Intra-event variability of Escherichia coli and total suspended solids in urban stormwater runoff. *Water Res.* **2012**, *46*, 6661–6670. [CrossRef] [PubMed]
9. Gorgoglione, A.; Bombardelli, F.A.; Pitton, B.J.L.; Oki, L.R.; Haver, D.L.; Young, T.M. Role of Sediments in Insecticide Runoff from Urban Surfaces: Analysis and Modeling. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1464. [CrossRef] [PubMed]
10. Ju, Y.L.; Kim, H.; Kim, Y.; Han, M.Y. Characteristics of the event mean concentration (EMC) from rainfall runoff on an urban highway. *Environ. Pollut.* **2011**, *159*, 884–888. [CrossRef]
11. Geonha, K.; Joonghyun, Y. Diffuse pollution loading from urban storm water runoff in Daejeon city, Korea. *J. Environ. Manag.* **2007**, *85*, 9–16. [CrossRef]
12. Oshawa, K. *Experimental Study on the Clogging of Voids of Porous Concrete and Porous Asphalt*; Technical Workshop 35th Kanto Branch Society of Civil Engineers: Tokyo, Japan, 2008.
13. Barrett, M.E.; Malina, J.F.; Charbeneau, R.J. *A Review and Evaluation of Literature Pertaining to the Quantity and Control of Pollution from Highway Runoff and Construction*; Bureau of Engineering Research, University of Texas at Austin, J.J. Pickle Research Campus: Austin, TX, USA, 1995.
14. Barrett, M.E.; Malina, J.F.; Charbeneau, R.J.; Ward, G.H. Characterization of highway runoff in Austin, Texas area. *J. Environ. Eng.* **2009**, *124*, 131–137. [CrossRef]
15. Kayhaniana, M.; Stransky, C.; Bayc, S.; Lau, S.L.; Stenstrom, M.K. Toxicity of urban highway runoff with respect to storm duration. *Sci. Total Environ.* **2008**, *389*, 386–406. [CrossRef] [PubMed]
16. Kayhaniana, M.; Fruchtmanb, B.D.; Gulliver, J.S.; Montanaro, C.; Ranieri, E.; Wuertz, S. Review of highway runoff characteristics: Comparative analysis and universal implications. *Water Res.* **2012**, *46*, 6609–6624. [CrossRef] [PubMed]
17. Modugno, M.D.; Gioia, A.; Gorgoglione, A.; Iacobellis, V.; la Forgia, G.; Piccinni, A.F.; Ranieri, E. Build-Up/Wash-Off monitoring and assessment for sustainable management of first flush in an urban area. *Sustainability* **2015**, *7*, 5050–5070. [CrossRef]
18. Herngren, L.; Goonetilleke, A.; Ayoko, G.A. Understanding heavy metal and suspended solids relationships in urban stormwater. *J. Environ. Manag.* **2005**, *76*, 149–158. [CrossRef] [PubMed]
19. Winston, R.J.; Hunt, W.F. Characterizing Runoff from Roads: Particle Size Distributions, Nutrients, and Gross Solids. *J. Environ. Eng.* **2017**, *143*, 1–12. [CrossRef]
20. Mayer, T.; Rochfort, Q.; Marsalek, J.; Parrott, J.; Servos, M.; Baker, M.; McInnis, R.; Jurkovic, A.; Scott, I. Environmental characterization of surface runoff from three highway sites in Southern Ontario, Canada. *Water Qual. Res. J. Can.* **2011**, *46*, 110–136. [CrossRef]
21. Gill, L.W.; Ring, P.; Neil, M.P.; Johnston, P.M. Accumulation of heavy metals in a constructed wetland treating road runoff. *Ecol. Eng.* **2014**, *70*, 133–139. [CrossRef]
22. Zhao, R.H. Accumulation and Purification Materials of Urban Rain Water. Ph.D. Dissertation, Tianjin University, Tianjing, China, 2010.
23. Hilliges, R.; Schriewer, A.; Helmreich, B. A three-stage treatment system for highly polluted urban road runoff. *J. Environ. Manag.* **2013**, *128*, 306–312. [CrossRef] [PubMed]
24. Boogaard, F.C.; Lucke, T.; Giesen, N.; van de Ven, F. Evaluate the infiltration performance of eight Dutch permeable pavements using a new full-scale infiltration testing method. *Water* **2014**, *6*, 2070–2083. [CrossRef]
25. Legret, M.; Colandini, V.; Marc, C.L. Effects of a porous pavement with reservoir structure on the quality of runoff water and soil. *Sci. Total Environ.* **1996**, *189–190*, 335–340. [CrossRef]

26. Fwa, T.F.; Lim, E.; Tan, K.H. Comparison of Permeability and Clogging Characteristics of Porous Asphalt and Pervious Concrete Pavement Materials. *Transp. Res. Rec.* **2015**, *2511*, 72–80. [CrossRef]
27. Hares, R.J.; Ward, N.I. Comparison of the heavy metal content of motorway storm water following discharge into wet bio-filtration and dry detention ponds along the London Orbital (M25) motorway. *Sci. Total Environ.* **1999**, *235*, 169–178. [CrossRef]
28. Selim, A.Q.; El-Midany, A.A.; Ibrahim, S.S. Microscopic evaluation of diatomite for advanced applications: Case study. In *Microscopy: Science, Technology, Applications and Education*; Méndez-Vilas, A., Díaz, J., Eds.; Formatex Research Center: Badajoz, Spain, 2010; pp. 2174–2181.
29. State Environmental Protection Administration of China (SEPA). *Standard of Environmental Quality for Surface Water*; GB 3838-2002; Environmental Science Press: Beijing, China, 2002.
30. Wang, Y.; Gao, C.; Yang, S. Research on runoff pollution characteristics and countermeasures at sensitive highway sites. *Pol. J. Environ. Stud.* **2016**, *25*, 813–821. [CrossRef]