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Non-point sources analyses in paved areas using statistical methods: case study of vortex type

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ABSTRACT

During a dry period, many kinds of pollutants are accumulated on the surface of paved roadways, and these are swept into nearby waterways when rain falls. Particularly when the pollutants are toxic heavy metals, the damage they cause to the water system could be significant. This study evaluated the removal efficiency of vortex-type treatment facilities in Yongin City, Gyeonggi Province, South Korea, over a 2-y period from 2006 to 2007. Grain-size analyses of Zn, Pb, and Cd, which are particulate materials and heavy metals, were also conducted. Monitoring results showed removal efficiencies ranging from 9% to 65% for TSS, 0–55% for BOD, 1–58% for TN and 1–68% for TP. In addition, analyses of the correlation between removal efficiency and precipitation characteristics by pollutant type showed that particulate materials have a high correlation with nutrient materials and heavy metals, while organic materials and nutrient materials also have a high correlation. A grain-size analysis of 1–100 μm diameter particles showed that fine particles contain large amounts of Zn and Pb, which are heavy metals.

Keywords: Event mean concentration (EMC); Non-point sources; Removal efficiency; Vortex-type; First-flush effect; Correlation coefficient; Grain-size analysis

1. Introduction

Non-point pollutants are swept into surface runoff, and as the amount of runoff varies substantially by season, it is difficult to predict and quantify the amount of pollutants. Variables such as weather conditions, geography, and land topography make controlling pollutants even more difficult [1–3]. A non-point pollutant contains various pollutants and is reported to have high pollutant load runoff [4,5]. In paved areas, the risk of pollution is higher than in unpaved areas because of the high rainfall runoff ratio and the discharge of high-concentration pollutants. As these pollutants contain high doses of toxic heavy metals from vehicles, their treatment is very important. Of the many heavy metals, Zn and Pb, which are commonly known to result from the movement of vehicles, are caused by intended and unintended discharges produced in the course of a variety of industrial activities [6–12]. Therefore, it is necessary to control non-point pollutants in paved areas to ensure the stable management of water quality.

The target water quality by water system for the four great rivers of Korea (Han River, Nakdong River, Keum River, Yongsan River) in terms of BOD is in the range of

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1–6 mg l^{-1}, and the pollutant load contribution by non-point pollutants of the four great rivers is 22–37% [13]. The contribution of these kinds of non-point pollution sources is rapidly increasing due to the expansion of basic environmental facilities, which means that the successful management of a water system is very difficult without controlling the non-point pollution sources that exist in river basins [14–19]. As such, the Ministry of the Environment drew up a "Plan for the Management of Non-point Pollution Sources" in 2002 and in 2004 issued a "Comprehensive Measure to Control Non-point Pollution Sources on the four Great Rivers as a way to Strengthen the Promotion of the Comprehensive Water Management Plan." [17].

This study attempted to investigate the removal efficiency of a vortex-type facility with non-point pollution sources within the rainfall runoff flowing into the facility installed under bridge G of Yongin City, Gyeonggi Province, South Korea. For this study, effluent and influent water flows occurring during rainfall were monitored and pollutants were analyzed, Event Mean Concentration (EMC) was calculated, and the attachment of heavy metals Zn, Pb, and Cd was checked by particle size (1–100 μm). (The EMC and removal efficiency extracted in this study could be used as basic data for future studies on non-point pollution sources within rainfall runoff from paved roads.)

2. Experimental methods

2.1. Facility principles

The vortex-type facility used in this study was installed for the purpose of treating non-point pollution sources within rainfall runoff. Fig. 1 shows that influent water is induced to spiral in the tub, creating an inertia force, and gravity pulls the sediment down and prevents it from rebounding upwards.

The treatment capacity of the vortex-type facility used in this study is 5000 m^3 d^{-1}, the screen's inner diameter is 750 mm, the screen's effective grain size is 2.4 mm, and the sump's inner volume is 1.27 m^3. The relevant data is shown in Table 1.

3. Monitoring location and methods

The monitoring location in this study is shown in Fig. 2. The affected water discharge area is the asphalt-paved area on the upper part of bridge G in Yongin City, Gyeonggi Province, South Korea. The size of the area is 1922 m^2. A vortex-type facility is installed between bridge piers. When rain falls, non-point pollutants are directly swept into the water stream.

4. Calculation of rainfall runoff EMC and removal efficiency

The concentration of pollutants used in calculating the load of pollutants from rainfall runoff varies depending on the amount of water flow, so EMC, which is a factor in these conditions, is used and is calculated with the monitored data as in Eq. (1) [3,20–22]. EMC can be calculated by dividing the total accumulated amount of pollutants discharged during the continuous rainfall period T with the total discharge amount and is utilized in the calculation of EMC of non-point pollution sources.

$$EMC = \frac{Discharged\ mass\ during\ an\ event}{Discharged\ volume} = \frac{\int_0^t C(t) \cdot Q_{TRu}(t)dt}{\int_0^t Q_{TRu}(t)dt} \quad (1)$$

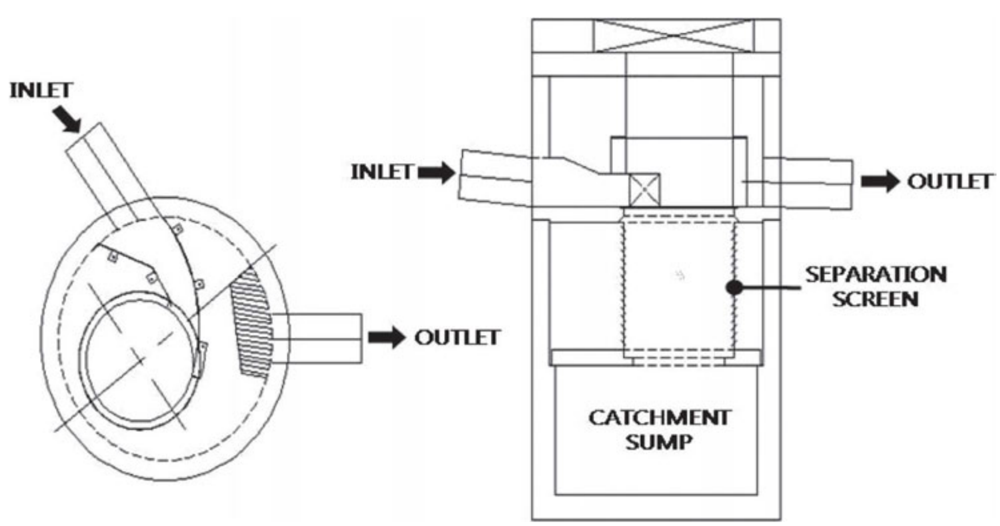

Fig. 1. Schematic diagram of vortex type facilities.

Table 1
Summary of vortex type facility use in this study

Summary of facility	
Facility site dimensions (m)	⇒ 5.0 × 6.0
Treatment capacity ($m^3\ d^{-1}$)	Q = 5000
Screen size (mm)	STS ∅ 750
Screen diameter (mm)	2.4
Sump capacity (m^3)	1.27

Note: STS = stainless steel.

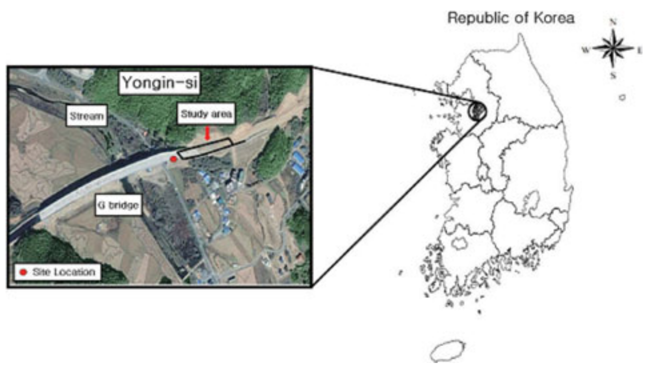

Fig. 2. Map showing the monitoring location and area. (a) Influent, (b) effluent.

Here, $C(t)$ and $Q_{TRu}(t)$ each represent the concentration and discharge ratio of the pollutant during the continuous rainfall period. In order to calculate the removal efficiency of a vortex-type facility, the monitored data are used in the calculation as shown in Eq. (2). Removal efficiency can be calculated by using the concentration and amount of effluent and influent flows during the continuous rainfall period T.

$$Removal\ Efficiency(\%) = \frac{\int_0^t C_{in}(t)\cdot Q(t) - \int_0^t C_{out}(t)\cdot Q(t)}{\int_0^t C_{in}(t)\cdot Q(t)} \times 100 \qquad (2)$$

Here, C_{in} and C_{out} each represent pollutant concentration of influent and effluent flows during the continuous rainfall period and $Q(t)$ represents the discharge ratio.

5. Statistical analysis

EMC and removal efficiency for each rainfall event were calculated using Eqs. (1) and (2). Then, a statistical analysis was conducted using SYSTAT version 9.0 to find the statistical representation of the calculated values. Here, the minimum, maximum, medium, average, variance, outliers, 90% confidence interval and interquartile range per percent are shown.

6. Results and discussion

6.1. The results of monitoring rainfall events

A total of 10 rainfall events were monitored during the 2-y period from 2006 to 2007, and the results of this monitoring are shown in Table 2. The antecedent dry days (ADD) are in the range of 1–45 d, the total rainfall is 6.0–60.5 mm, the runoff duration is 3.0–11.4 h, and the average rainfall intensity is 1.2–5.4 mm h^{-1}.

6.2. Concentration characteristics of pollutants

In paved areas, the impervious ratio is relatively high, which means that there will be more rainfall runoff

Table 2
Event table for monitored event

Event no.	Event date (yy/mm/dd)	ADD (d)	Total rainfall (mm)	Storm duration (h)	Runoff (influent time)	Runoff (effluent time)	Avg. rainfall intensity (mm h^{-1})
E-1	06/06/22	5	7.5	5.6	03:07 AM	03:16 AM	1.35
E-2	06/06/29	2	13.5	6.2	19:18 PM	19:22 PM	2.19
E-3	06/08/17	18	6.5	3.0	01:51 AM	01:56 AM	2.15
E-4	06/09/05	8	11.0	4.2	00:16 AM	00:20 AM	2.62
E-5	06/10/22	45	6.0	5.0	12:25 PM	14:30 PM	1.20
E-6	07/03/05	1	33.5	11.4	14:00 PM	14:05 PM	2.95
E-7	07/04/30	9	16.5	3.9	23:31 PM	23:40 PM	4.23
E-8	07/05/17	4	60.5	5.0	13:45 PM	13:46 PM	12.10
E-9	07/05/24	6	48.0	9.9	15:26 PM	15:30 PM	4.85
E-10	07/06/28	2	6.0	3.9	09:50 AM	09:51 AM	1.54

Note: ADD = Antecedent Dry Days.

compared to other land usages, and that non-point pollutants accumulated during the non-rainfall period will be swept into the water system all at once [24]. Figs. 3 and 4 show the appearance concentration of influent and effluent samples from a vortex-type facility and their representation on hydro- and polluto-graphs. The first-flush phenomenon that can be observed in rainfall runoff from paved areas can be seen by looking at the appearance concentration of samples as well as quantitatively on the hydro- and polluto-graphs [23–25].

Fig. 3. Appearance concentration of monitoring sample (E-7). (a) Influent, (b) effluent.

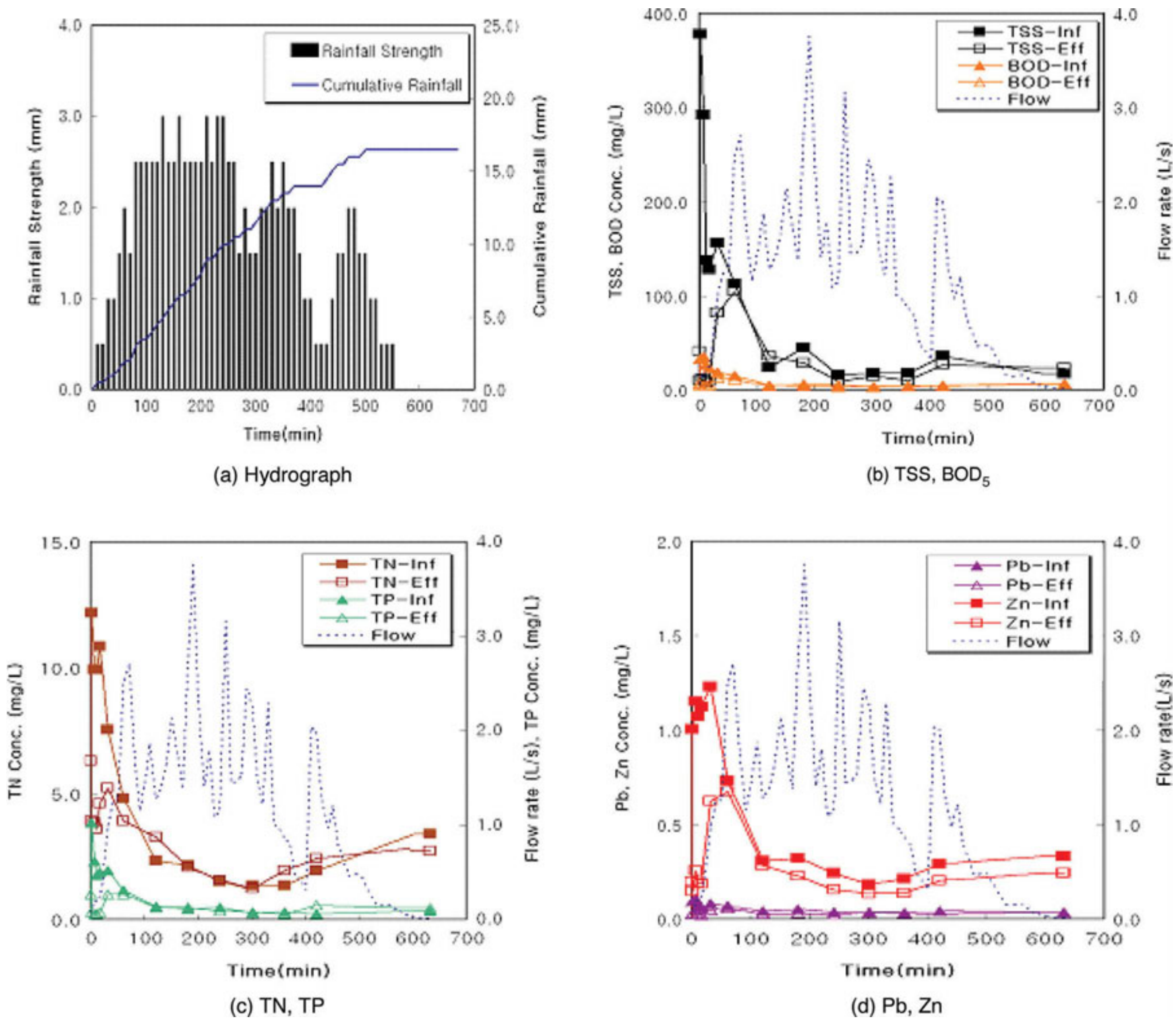

Fig. 4. Hydro-and polluto-graphs of monitoring sample. (a) Hydrograph, (b) TSS, BOD_5, (c) TN, TP, (d) Pb, Zn.

6.3. EMCs statistical analysis

EMC of each pollutant was calculated using the monitored data from a total of 10 rainfall events, and the results are shown in Fig. 5.

EMC data of influent water shows a range of 11.60–230.90 mg l^{-1} for TSS EMC, 4.58–31.90 mg l^{-1} for BOD EMC, 1.23–9.20 mg l^{-1} for TN EMC, and 0.12–1.55 mg l^{-1} for TP. With regard to heavy metals, the EMCs of Pb and Zn stay within the ranges of 0.00–0.15 mg l^{-1} and 0.12–0.96 mg l^{-1}, respectively. In the case of the effluent water, TSS EMC stays in the range of 5.10–170.60 mg l^{-1}, BOD EMC in the range of 3.24–27.20 mg l^{-1}, TN EMC in the range of 0.84–9.10 mg l^{-1}, and TP in the range of 0.11–1.35 mg l^{-1}. EMCs for the heavy metals Pb and Zn each stay in the ranges of 0.00–0.15 mg l^{-1} and 0.07–0.85 mg l^{-1}, respectively. No Cd was detected during the 10 monitoring events, and this is considered to be due to the fact that the bridge is fairly new and that there is not so much traffic. In the 95% confidence interval of the EMCs for influent non-point pollutants, TSS stays in the range of 22.64–132.08 mg l^{-1} and BOD stays the range of 6.96–18.67 mg l^{-1}, with TN and TP staying in the ranges of 2.23–5.97 mg l^{-1} and 0.12–0.74 mg l^{-1}, respectively. In the 95% confidence interval of the EMCs for effluent non-point pollutants, TSS stays in the range of 14.84–86.47 mg l^{-1} and BOD stays the range of 4.42–14.39 mg l^{-1}, with TN and TP staying in the ranges of 1.69–5.03 mg l^{-1} and 0.05–0.58 mg l^{-1}, respectively.

6.4. Statistical analysis of removal efficiency

Calculated removal efficiencies by pollutant based on the results of a total of 10 monitoring events are shown in Table 3.

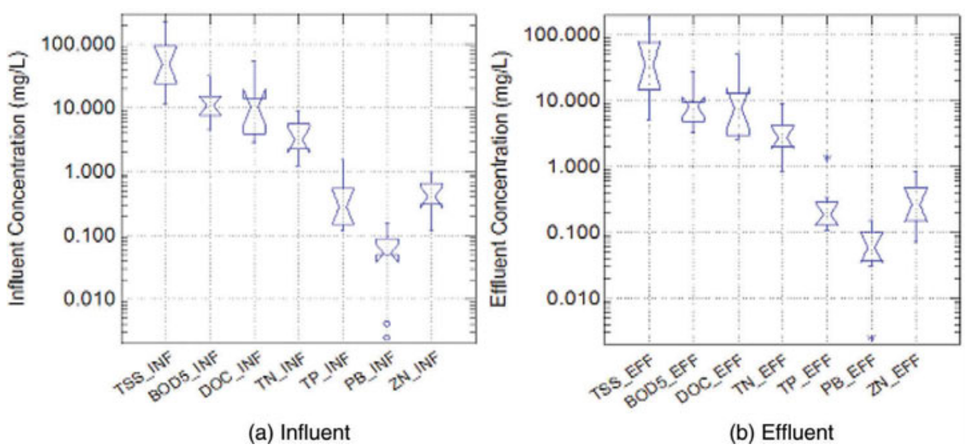

Fig. 5. Statistical summaries of EMCs. (a) Zn, (b) Pb.

Table 3
Statistical summaries of the pollutants removal efficiency for the each rainfall event

Parameters (%)	Basic statistics					Confidence interval	
	Min.	Max.	Median	Mean	St. dev.	95% Upper	95% Lower
TSS	8.70	64.90	26.35	32.48	19.82	46.66	18.31
BOD_5	0.40	54.70	27.35	26.11	18.64	39.44	12.78
DOC	2.00	73.30	11.15	21.69	23.29	38.35	5.03
TN	0.70	58.10	14.85	17.73	17.67	30.37	5.09
TP	0.70	65.50	18.70	23.61	22.96	40.03	7.19
Oil and grease	0.00	97.50	0.00	25.06	36.27	51.01	−0.89
Pb	0.00	100.00	6.95	25.71	39.89	54.25	−2.83
Zn	0.30	81.30	23.15	28.00	24.64	45.62	10.38
Cd	0.00	0.00	0.00	0.00	0.00	0.00	0.00

A look at the removal efficiencies with regard to influent water shows that TSS stays in the range of 8.7–64.9%, BOD in the range of 0.4–54.7%, TN in the range of 0.7–58.1% and TP in the range of 0.7–67.5%. For heavy metals, and oil and grease, the efficiency range is wide, which is considered to be due to the fact that the amount of pollutants contained in rainfall runoff is small, and thus, the removal by the facility is small or negligible, resulting in a wide efficiency range.

6.5. Analysis of correlation between removal efficiency and rainfall characteristics

The correlation between rainfall characteristics and removal efficiency by pollutant was analyzed in order to identify factors affecting removal efficiency for non-point pollutants produced on the upper part of the bridge during rainfall, and the results of this analysis are shown in Table 4.

A close look at the results reveals that, in particulate materials, there is high correlation between nutrient materials and heavy metals. This is considered to be due to the fact that other non-point pollutants are detached when particulate materials are induced by rainfall. Organic materials and nutrient materials show a high correlation. In addition, removal efficiencies of DOC, TN, and TP show a relatively high correlation with ADD. Oil and grease show a certain level of correlation with the continuous rainfall period, and this is considered to be due to the fact that there is a continuous discharge from vehicles during this period.

6.6. Result of grain-size analysis

Most of the heavy metals found in rainfall runoff are attached to particulate materials, and the concentration of heavy metals tends to increase as the size of a particle decreases. This is due to the fact that fine particles have relatively large surface areas and high cation exchange capacities [26,27]. Consequently, it is thought that other pollutants could be removed through the effective control of particulate materials. In addition, past studies have reported that pollutants such as nutrient materials and heavy metals are more likely to be attached to fine particles than coarse particles and discharged [1,8,28,29].

This study conducted analyses on the heavy metals Zn, Pb, and Cd with 1–100 μm grain-size particles. However, in a total of 10 monitoring events no Cd was detected, and this is considered to be due to the fact that the construction period for bridge *G* where the monitoring was conducted was short, and there was not much traffic. So in this study, an analysis of Zn and Pb, excluding Cd, was conducted, and the concentrations of each influent sample particle were analyzed. Fig. 6 shows the analysis results both from the monitoring data and from existing papers, where Zn shows high concentrations in particles under 50 μm in diameter and low concentrations in particles with diameters of 50–100 μm and above 100 μm. In the case of Pb, unlike Zn, there was high concentration in particles under 50 μm in diameter, and in 50–100 μm particles concentration was lower than in 50 μm particles, but showed similar values. In particles larger than 100 μm in diameter, concentration was low [30–32]. This means that the heavy metals Zn and Pb are attached to fine particles.

Table 4
Correlation coefficients results for removal efficiency of storm variables and pollutants

	TSS	BOD	DOC	TN	TP	O_G	TOT_Pb	TOT_Zn	ADD	Rainfall	AVR	STD
TSS	1											
BOD	0.27	1										
DOC	0.14	0.80	1									
TN	0.52	0.80	0.87	1								
TP	0.61	0.76	0.68	0.71	1							
O_G	0.40	0.31	0.37	0.40	0.21	1						
TOT_Pb	0.51	0.30	0.42	0.52	0.16	0.17	1					
TOT_Zn	0.58	0.03	0.28	0.50	0.05	−0.22	−0.27	1				
ADD	0.13	0.30	0.66	0.62	0.54	−0.09	0.08	0.33	1			
Rainfall	0.40	0.04	0.08	0.11	0.30	0.19	−0.32	0.17	−0.35	1		
AVR	0.49	0.02	0.12	0.07	0.26	0.12	−0.07	0.16	−0.35	0.95	1	
STD	0.33	0.03	0.03	0.02	0.43	0.30	−0.50	0.04	−0.35	0.81	0.60	1

Note: ADD = Antecedent Dry Days, AVR= Average Rainfall Intensity (mm h^{-1}), STD = Storm Duration (h).

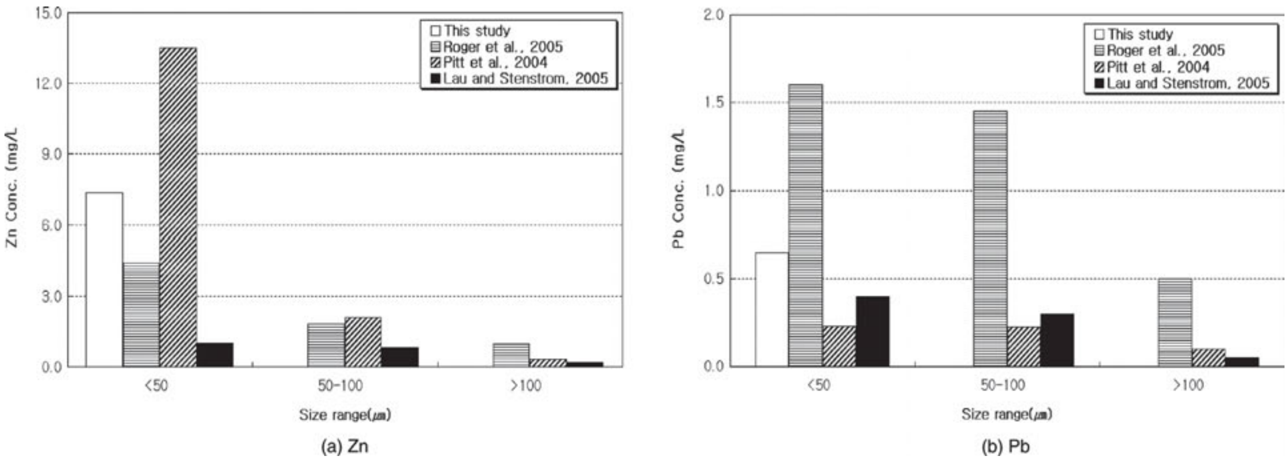

Fig. 6. Quantities of metals according to the particular sediment size ranges of monitoring samples.

7. Conclusions

This study summarized the removal efficiency of a vortex-type treatment facility with non-point pollutants discharged during rainfall in paved areas, and looked at the correlation between pollutants and grain-size analyses, and came to the following conclusions:

- Influent water shows the first-flush effect in the early stage of a rainfall period, and it weakens in concentration as the rainfall continues.
- For heavy metals, and oil and grease, the efficiency range is wide, which is considered to be due to the fact that the amount of pollutants contained in rainfall runoff is small, and thus, the removal by the facility is small or negligible, resulting in a wide efficiency range.
- An analysis of correlation between removal efficiency and rainfall characteristics for each pollutant reveals that in particulate materials there is high correlation between nutrient materials and heavy metals. This is considered to be due to the fact that other non-point pollutants are detached when particulate materials are induced by rainfall. Organic materials and nutrient materials also show high correlation. Oil and grease show a certain level of correlation with the continuous rainfall period, and this is considered to be due to the fact that there is a continuous discharge from vehicles during this period.
- Analyses of the concentration of fine particles (1–100 μm) show a high concentration of Zn in particles under 50 μm in diameter and a low concentration in particles 50–100 μm in diameter, whereas there was a high concentration of Pb in particles under 100 μm in diameter, and a low concentration in particles above 100 μm in diameter. This shows that the heavy metals Zn and Pb tend to be attached to fine particles (1–100 μm).

Symbols

$C(t)$ — Concentration of pollutant during continuous rainfall period.
C_{in} — Pollutant concentration of influent flow during the continuous rainfall.
C_{out} — Pollutant concentration of effluent flow during the continuous rainfall.
$Q(t)$ — Discharge ratio.
$Q_{TRu}(t)$ — Concentration of discharge ratio of pollutant during continuous rainfall period.

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