

Determination of the removal efficiency of a vortex-type facility as a best management practice using the dynamic event mean concentration: a case study of a bridge in Yong-In city in Korea

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Abstract Thus far, the removal efficiency of non-point-pollution source removal facilities has been evaluated for individual rainfall events. However, as the removal efficiency for part of a single rainfall event has not been evaluated, adapting the removal facilities for these concentrations is imprecise. Of 18 rainfall events, the removal efficiency of a vortex-type facility as a BMP (Best Management Practice), a non-point-pollution source removal method, was assessed in this study in four assessment techniques and analyzed. In addition, the efficiency was assessed for the concentration using dynamic EMC (Event Mean Concentration). At a higher concentration, the efficiency becomes higher in terms of the TSS, COD, and TP results. In the case of TP, the concentration range of 0~2 mg/L showed the highest efficiency. In the case of Zn, low efficiency was shown in a concentration range of 0.2~0.6 mg/L.

Keywords Dynamic EMC · Non-point sources · Removal efficiency · Vortex-type facility

Introduction

Regulations pertaining to water pollution in Korea are managed for point-pollution sources such as domestic sewage and industrial sewage sources. Therefore, the improvement of the water quality of a river is limited, despite the considerable amount of progress that has been made in this area (Rahman and Al Bakri 2010). This situation has arisen because pollutants are induced into a river or a lake in large amounts from unspecified pollution sources known as non-point-pollution sources more than they are from careless management of point-pollution sources, though management of non-point-pollution sources is urgent along with regulations of point-pollution sources in order to improve the overall water quality (Bhardwaj and Singh 2011; Andrea et al. 2010).

Non-point pollutants are unspecified pollution substances occurring from various uses of the ground when raining. These types of pollutants are affected by rain and become discharged with runoff water from the ground surfaces (Dongquan et al. 2009; Wang et al. 2010). Non-point pollutants flow into rivers and thus can induce a toxic environment for the organisms living in the water or can cause damage to the ecosystem (Jalali and Kolahchi 2009). It has also been reported that management and handling require complicated work and that pollutant loadings are much higher than those from a sewage treatment plant (Chiew and McMahon 1999; Sansalone and Buchberger 1997; Wang et al. 2006).

In particular, non-point pollutants produced in a city area are highly concentrated compared with other characteristics of ground use. Moreover, there is higher possibility in these areas that harmful chemical substances such as oil and heavy metals will be induced. This will lead to problems when these substances flow into rivers through drain

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pipes during rainfall events (El-Hasan et al. 2006). In addition, as society becomes more urban, the amounts of such pollutant discharges grow into large amounts early on, complicating efforts to manage pollution (Barrett et al. 1998; Becher et al. 2000).

Many removal facilities are under development, including special types of devices and natural efforts, in an effort to manage non-point-pollution sources. However, there is some difficulty in assessing the efficiency of a removal facility as discharge forms can vary with the characteristics of non-point-pollution sources, which themselves differ from point-pollution sources. Moreover, there are many different handling methods used by removal facilities. Therefore, methods of efficiency assessment must be differentiated according to the removal facility. Removal facilities for non-point-pollution sources can largely be divided into device-type and natural-type facilities. The device types include screens, filters, vortices, coagulating sedimentation handling methods, and biological types depending on the method of handling. The nature types include retention facilities, artificial wetlands, penetration facilities, and vegetation-type facilities. The removal facility for non-point-pollution sources investigated here is a vortex-type removal facility, which is a device-type facility. It separates influent continuously and removes non-point pollutants by precipitating the pollutants.

This study assessed the removal efficiency of non-point-pollution sources by targeting the non-point-pollution sources of a bridge using a vortex facility. Four existing methods are assessed, and a method of assessing efficiency using dynamic EMC (Event Mean Concentration), which offers high efficiency during individual events, is suggested. Thus far, no clearly proven method for assessing efficiency during the removal of non-point pollutants has been developed, as changes in the removal efficiency vary according to the type of removal method used and the drainage basin and precipitation conditions under which the method is used. Therefore, this study assesses five assessment methods to evaluate the efficiency of each. Thus, this study can serve as useful data for assessing an optimal management method for non-point pollutants in the future.

Study method

Summary of facility

The vortex-type facility used in this study is a removal device installed to handle non-point pollutants within runoff water when raining. It is displayed in Fig. 1 in diagram form. The removal fundamentals are that inertial

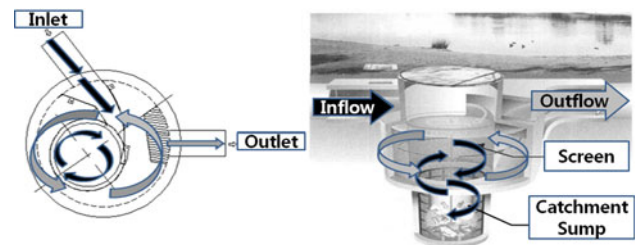


Fig. 1 Schematic diagram of the vortex-type facility

Table 1 Summary of the vortex-type facility used in this study

Vortex-type facility	Treatment capacity (m ³ /day)	Screen size (mm)	Screen diameter (mm)	Sump capacity (m ³)
	5,000	750	2.4	1.27

force is created in a particle by inducing influent water to be separated via deflection in a vortex-type facility, after which gravity allows precipitation over in time. The treatment capacity of the vortex-type facility tested here is 5,000 m³/day, the screen size is 750 mm, the screen diameter is 2.4 mm, and the sump capacity is 1.27 m³. A summary is given in Table 1.

Monitoring

This study installed a removal facility in 2005 and conducted monitoring trials 18 times from 2006 to 2007 on Kisun Bridge, which is located at Unhak-dong, Yongin city, in Gyeonggi province of Korea. The backwater basin was a 100% paved region of 3,200 m². The location and status are shown in Fig. 2 and Table 2. A weir was installed to ensure effective monitoring. Sampling procedures were prepared before a rainfall event, and the preparation for monitoring was completed by that time. Measurement of the discharge was taken by the direct measurement of the discharge amount that was caught for a certain period of time out of every 10 min. For sampling, to analyze the water quality, the first sampling process was done immediately after an inflow and discharge had occurred. Water was sampled in 5-min intervals in the early part, 1-h intervals for 1–3 h, and in intervals of 1–3 h after that by measuring the turbidity. The sampled water was transported to a laboratory after the rain stopped, and tests were conducted in which the samples were divided into the parameters of the substances of particulate matter, organic matter, nutrient salts, and heavy metals. Analyses of water quality were conducted for TSS, BOD₅, COD, TN, TP, Cd, Pb, and Zn parameters, and they applied the Standard Method (APHA 1998) as the measurement method of each parameter.

Fig. 2 Map showing the monitoring location



Table 2 Characteristics of the monitoring location

Monitoring site	Landuse	Area (m ²)	Pavement type
Bridge	Transportation landuse area	3,200	100% impervious

Assessment of the removal efficiency

There were four levels of removal efficiency according to the assessment method of removal efficiency. This was done in order to assess the removal efficiency specifically for vortex facility. The first method is the ER (Efficiency Ratio) method. It calculates the simple arithmetic mean for the removal efficiency per precipitation condition. It is expressed as Eq. 1 (US EPA 1983). The second method is the SOL (Summation of Total Incoming Loads) method. This method divides the total amount of pollutants removed in the facility by the total loading amount; it is expressed as Eq. 2 (US EPA 2002). The third method is the ROL (Regression of Loads) method of assessing. It uses a trend line of the annual inflow and discharge. It is expressed as Eq. 3 (Martin and Smoot 1986). The fourth method is the ROF (Rainfall of Frequency) method of assessment. It uses the occurrence frequency per precipitation class, and it is expressed as Eq. 4 (Choi et al. 2008).

$$ER (\%) = \frac{\sum_{i=1}^N \text{Removal efficiency}_i}{N} \tag{1}$$

$$SOL (\%) = \frac{\sum_{i=1}^N \text{inflow mass}_i - \sum_{i=1}^N \text{outflow mass}_i}{\sum_{i=1}^N \text{inflow mass}_i} \tag{2}$$

$$ROL (\%) = (1 - \beta) \times 100, \beta = \text{The slope of the trend} \tag{3}$$

$$ROF (\%) = \sum_{i=1}^{N_R} (\text{Removal efficiency}_i \times \text{Rainfall Frequency}_i) \tag{4}$$

$$N_R = \text{Number of rainfall ranges} \tag{5}$$

Assessment of the removal efficiency using dynamic EMC

The concentration of the pollutants used in assessing the loadings of the pollutants discharged from rain is termed the EMC. It is assessed with the monitoring results via Eq. 5. EMC can be calculated by dividing the entire amount of accumulated pollutants that are discharged for the total continuous raining time *T* by the total discharge amount. It is very useful for assessing average concentrations from non-point-pollution sources. *C(T)* and *Q_{TRa}(T)* here refer to the concentration of the pollutants and the discharge rate pertaining to the continuous raining time *T*

Table 3 Event table in the paved areas

Event no.	Event date		ADD (day)	Total rainfall (mm)	Runoff duration (h)	Avg. rainfall intensity (mm/h)
	Year	Month-date				
E-1	2006	06.06.22	5	7.5	5.5	1.36
E-2		06.06.29	2	13.5	6.2	2.18
E-3		06.08.17	18	6.5	3.0	2.17
E-4		06.09.05	8	11.0	4.2	2.62
E-5		06.10.22	45	6.0	5.0	1.20
E-6		07.03.04.	1	33.5	11.4	2.94
E-7	2007	07.04.30	9	16.5	10.5	1.57
E-8		07.05.17	4	60.5	11.2	5.40
E-9		07.05.24	6	48.0	9.9	4.85
E-10		07.06.28	2	6.0	3.9	1.54
E-11		07.07.19	2	49.5	7.0	7.07
E-12		08.03.22	9	22.5	11.5	1.96
E-13	2008	08.05.28	7	41	8	5.13
E-14		08.06.02	5	28.5	8	3.56
E-15		08.06.28	7	5	0.65	7.69
E-16		08.07.02	3	15.5	8.8	1.76
E-17		08.07.19	8	72	12	6.00
E-18		08.07.24	2	149.5	16.7	8.98

ADD antecedent dry day

(Sansalone and Cristina 2004; Huang et al. 2007; Yoon et al. 2010).

$$EMC = \frac{\int_q^T C(T) \cdot Q_{TRa}(T) dt}{\int_q^T Q_{TRa}(T) dt};$$

$$\text{Dynamic EMC (mg/L)} = \frac{\sum_{i=0}^{t-t} c(t) \cdot q_{run}(t)}{\sum_{i=0}^{t-t} q_{run}(t)} \quad (6)$$

The dynamic EMC result of Eq. 6 shows the EMC value of the pollutants that are discharged during a specific rain event time t (Kim et al. 2007). In other words, EMC is the average concentration of discharged pollutants according to the total continuous rain time. However, regarding the dynamic EMC, the concentration will change according to the continuous raining time. Efficiency according to the dynamic EMC result is expressed as Eq. 7 when using dynamic EMC.

Removal efficiency of Dynamic EMC (%)

$$= \frac{\sum_{i=0}^{t-t} c_{in}(t) \cdot q_{run}(t) - \sum_{i=0}^{t-t} c_{out}(t) \cdot q_{run}(t)}{\sum_{i=0}^{t-t} c_{in}(t) \cdot q_{run}(t)} \quad (7)$$

Conclusion and considerations

Results of monitoring

Monitoring of precipitation conditions was conducted 18 times from June 2006 to August 2008. These results are tabulated in Table 3. The ADD (Antecedent Dry Days) before rain showed a large range of 1~45 days, and various rainfall events were monitored. The total rainfall for each ranged from 5.0 to 149.5 mm. The rainfall duration had a range of 0.65~16.7 mm per hour, and the average rainfall intensity had a range of 1.20~8.98 mm/h. Figure 3 shows a hydro- and polluto-graph; the first flush effect, where highly concentrated pollutants are discharged at the early time of rain discharge and where the concentration of pollutants rapidly falls as time passes, can be determined via the change in the concentration of the pollutants and the discharge flux.

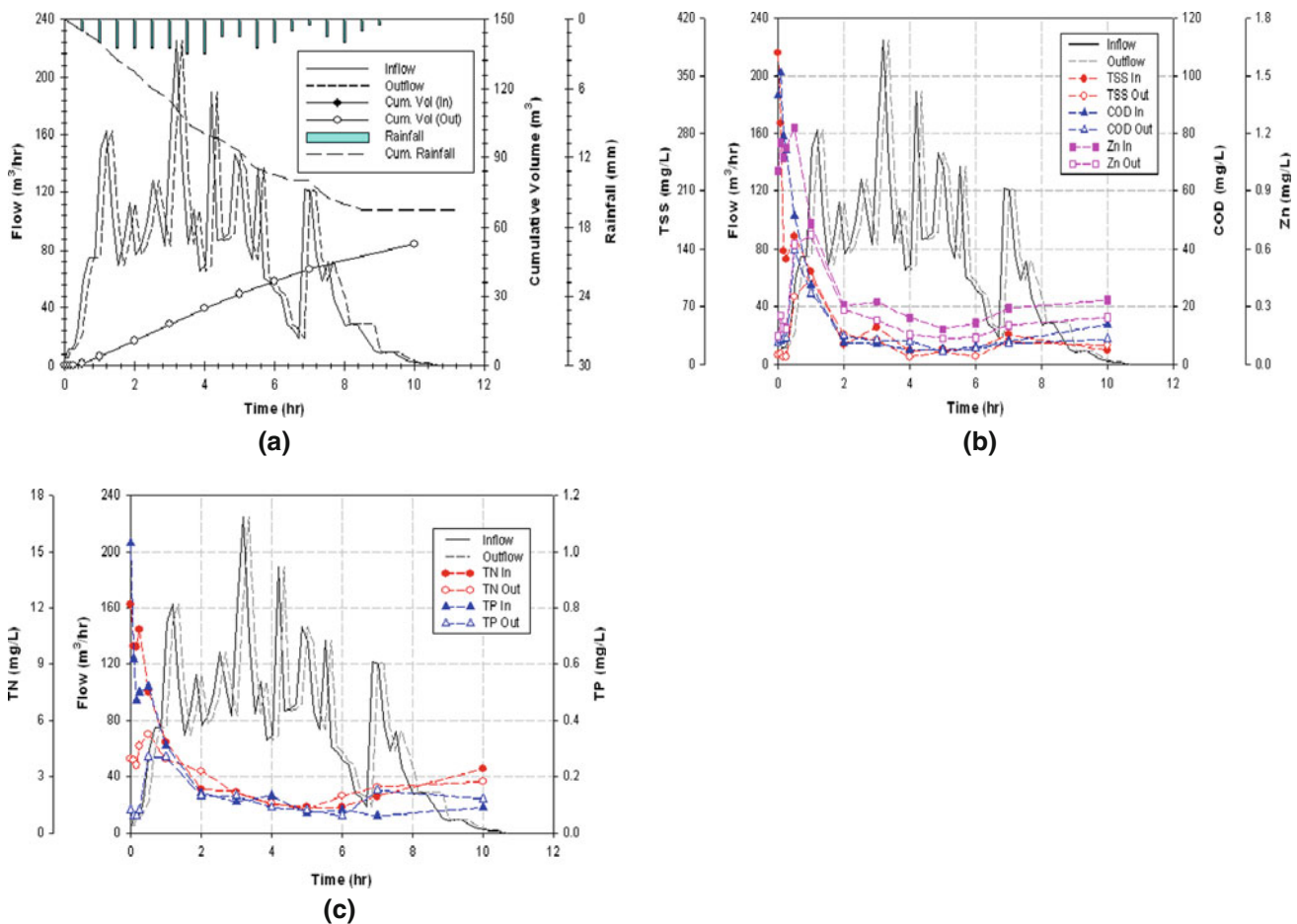


Fig. 3 Polluto-/hydro-graph of event 7. **a** Hydro graph; **b**TSS, COD, Zn; **c** TN, TP

Table 4 Results of basic statistics for the Vortex-type facility efficiency

Parameters	N	Median (%)	Mean (%)	95% CI		Standard deviation
				Lower	Upper	
TSS	18	30.0	34.7	23.0	46.4	23.6
COD	18	24.3	29.1	17.6	40.6	23.1
TN	16	16.8	24.4	12.2	36.6	22.9
TP	16	29.4	34.7	20.3	49.0	26.9
Zn	16	30.0	36.4	23.0	49.8	25.2

Table 5 Removal efficiency using the four methods assessed in this study

Parameters	Method (%)				
	ER	SOL	ROL	ROF	Average
TSS	34.7	32.8	40.0	42.6	37.53
COD	29.1	25.1	17.5	30.8	25.63
TN	24.4	17.6	25.4	22.0	22.35
TP	34.7	30.3	53.3	34.2	38.13
Zn	36.4	30.3	47.5	37.4	37.9

Assessment of the removal efficiency

The removal efficiency is summarized in Table 4. The vortex-type facility installed at Woonhak-dong in Yongin stipulates particulate substances as the main removal target substance. The removal efficiency for TSS was 0.9~70.4%, which suggests that there is a considerable change in the range according to the characteristics of the precipitation. The range of the minimum efficiency and the maximum efficiency for handling organic matter, nutritive salts, and heavy metals was broad, and the value of the average deviation was more than 20 for all parameters. A conference interval of 95% was noted for the large range of most of the parameters. Moreover, the removal efficiency per precipitation event showed considerable changes due to precipitation condition and season in which the event occurred. This shows that suggesting an assessment method for the removal efficiency of non-point pollutants is difficult.

Removal efficiency for the four assessment methods

In Table 5, the removal efficiency of each parameter is assessed for the four methods of assessing the removal efficiency. The ER method out of the four methods is generally used in many papers, and the value of the removal efficiency can be underrated or overrated, as it does not consider the statistical meaning. The SOL method uses the results of the total loading; it has a disadvantage in

Table 6 Removal efficiency using dynamic EMCs

TSS	COD		TN		TP		Zn	
	Concentration (mg/L)	Efficiency (%)	Concentration (mg/L)	Efficiency (%)	Concentration (mg/L)	Efficiency (%)	Concentration (mg/L)	Efficiency (%)
0~50	0~10	38.9	0~2	18.5	0~0.2	25.2	0~0.2	41.0
50~100	10~20	34.1	2~4	15.5	0.2~0.4	27.0	0.2~0.4	26.9
100~150	20~30	39.5	4~6	13.3	0.4~0.6	45.5	0.4~0.6	25.5
Over 150	Over 30	57.6	Over 6	0.4	Over 0.6	50.0	Over 0.6	49.7

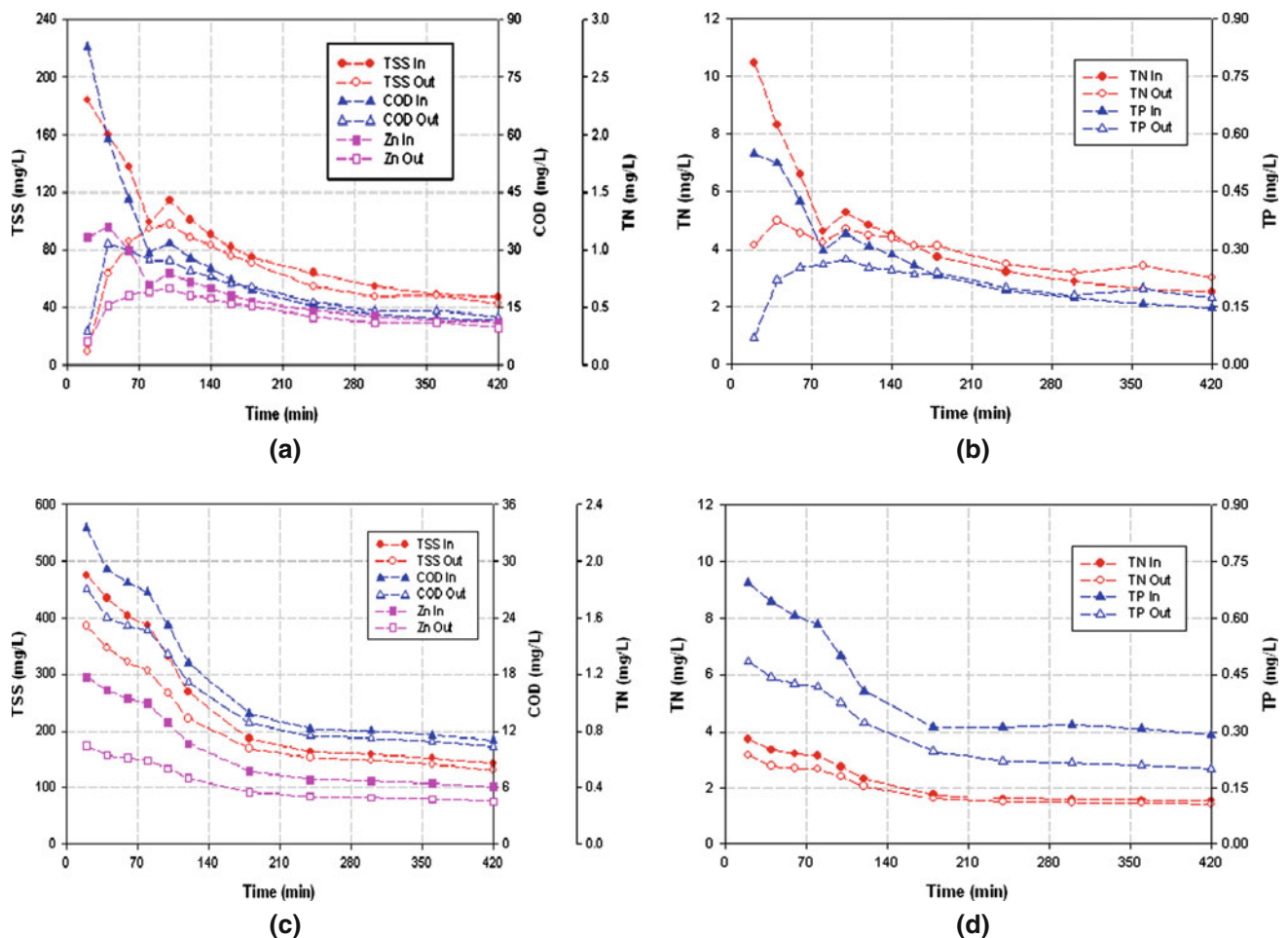


Fig. 4 Hydro-/polluto-graph of dynamic EMC. **a** TSS, COD, Zn of event 7; **b** TSS, TP of event 7; **c** TSS, COD, Zn of event 8; **d** TSS, TP of event 8

that it can be greatly affected by a large precipitation event among the monitoring results. The ROL method assesses a trend line based on data that are monitored in real time; therefore, it cannot be applied widely. As the ROF method includes the frequency of precipitation, it may return a low value of the removal efficiency for precipitation even when precipitation was high. It is more effective than the other three methods, but it may return a low removal efficiency value for a precipitation event for an effective or particularly strong raining.

For TSS and COD, the assessment method of the removal efficiency that showed the best removal efficiency was ROF, whereas the methods that showed the lowest removal efficiency were SOL and ROL. For the cases of TN, TP, and Zn, ROL had the best efficiency and SOL had the lowest value.

The range of removal efficiency of TSS obtained for the four removal efficiency assessment methods was 32.8~42.6%. This range was 17.5~30.8% for COD, 17.6~25.4% for TN, 30.1~53.3% for TP, and lastly

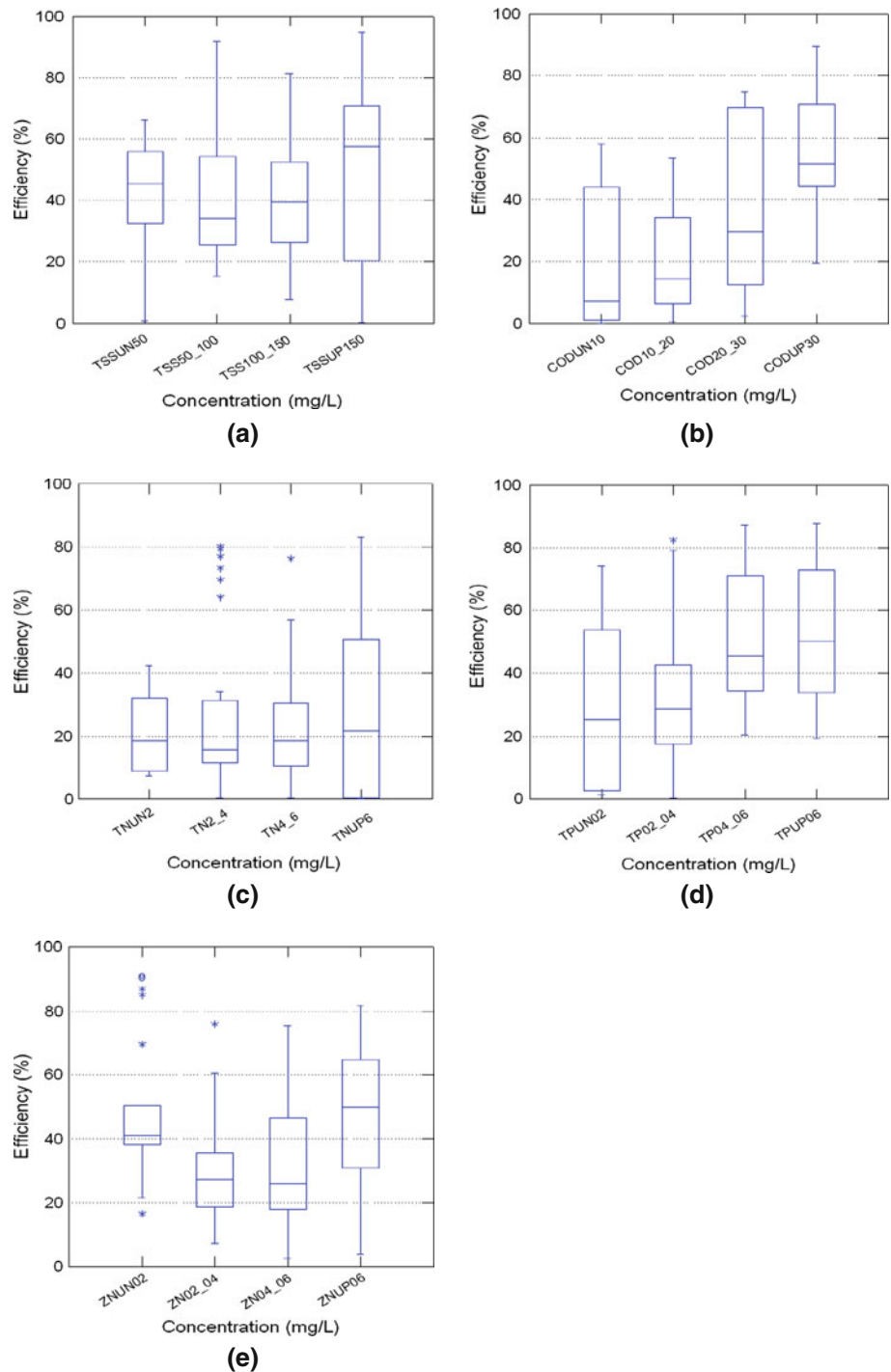
30.3~47.5% for Zn. The average value of the removal efficiency of the four methods was assessed, and the results were found to be 37.1% for TSS, 31.0% for BOD, 21.7% for TN, 37.0% for TP, and 37.9% for Zn.

Assessment of the efficiency using dynamic EMC

Table 6 shows an assessment of the efficiency using dynamic EMC. Dynamic EMC was assessed in the early stage for about 20 min. After 120 min had passed, dynamic EMC was flexibly assessed according to the water sampling status. Figure 4 shows in the results. According to dynamic EMC, a dramatic drop in the concentration occurred. Efficiency was organized according to dynamic EMC, and the results were divided into four instances considering each frequency.

The removal efficiency per EMC was organized using a statistical method, as shown in Fig. 5. The intermediate value per concentration is organized in Table 6. Considering the change range of the removal efficiency per dynamic

Fig. 5 Statistical summaries of efficiency using dynamic EMC. **a** TSS; **b** COD; **c** TN; **d** TP; **e** Zn



EMC concentration, the particulate substance TSS result showed the smallest change range when the concentration is less than 50 mg/L. In addition, it showed a change range with the highest removal efficiency and the greatest removal efficiency when the concentration exceeded 150 mg/L. For organic matter COD, the range of removal efficiency was at its smallest when the concentration was between 10~20 mg/L and over 30 mg/L; as the concentration

increased, the intermediate value also increased. Nutrient salts showed different appearances in that TN had the lowest intermediate value when the concentration exceeded 6 mg/L; the range of removal efficiency was also large. However, TP had largest range of removal efficiency when the concentration was less than 0.2 mg/L. In addition, the intermediate value of the removal efficiency was lower than it was for other concentrations. A heavy metal, Zn, showed

stable removal efficiency in most cases when the concentration was less than 0.2 mg/L; here, the range change of the removal efficiency increased as the concentration increased. It showed the highest efficiency at a high concentration of 0.6 mg/L.

Conclusion

- As a result of examining the removal efficiency of each parameter via four removal efficiency assessment methods using monitoring results of 18 events at a vortex-type facility, a difference in the efficiency levels of the methods were noted. For the average efficiency of each method, TSS showed 37.1%, BOD showed efficiency of 31.0%, TN showed 21.7%, TP showed 37.0%, and Zn showed 37.9%.
- As a result of organizing the efficiency for each EMC using a statistical method, TSS showed stable efficiency overall and showed the highest removal rate for a high concentration. COD and TP had high efficiency as the concentration increased, and TN and Zn showed different efficiency levels according to dynamic EMC. With this result, it will show optimal efficiency when vortex-type facilities are installed in areas where pollutants are discharged at high concentrations within precipitation events in the future. The findings of this study demonstrate that the optimal level of efficiency will be gained when the dynamic EMC result exceeds 120 mg/L and 30 mg/L for TSS and COD, respectively, with excesses of 0.6 mg/L for TP and ZN and a result less than 0.2 mg/L for TN when a dynamic vortex-type removal facility is installed in areas where pollutants are discharged at high concentrations.

These results are expected to be used as valuable data for assessing the optimal management method for non-point pollutants in the future.

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