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Application of coagulation process for the treatment of combined sewer overflows (CSOs)

Je Chan Jeon[a], Koo Ho Kwon[a], Lee Hyung Kim[b], Joon Ha Kim[c], Yong Jun Jung[d], Kyung Sok Min[a,]*

[a]*Department of Environmental Engineering, Kyungpook National University, 1370, Sankyuk-dong, Buk-gu, Daegu 702-701, South Korea*
Tel. +82 53 950 6581; Fax: +82 53 959 7734; email: ksmin@knu.ac.kr
[b]*Department of Civil and Environmental Engineering, Kongju National University, 275 Budaedong, Seobukgu, Cheonan, Chungnamdo 331-717, South Korea*
[c]*Gwangju Institute of Science and Technology (GIST), School of Environmental Science and Engineering, Gwangju 500-712, South Korea*
[d]*Department of Environmental Engineering, Catholic University of Pusan, 9 Bugok3-dong, Geumjeong-gu, Busan 609-757, Korea*

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ABSTRACT

Nonpoint source pollutions discharged with stormwater runoff during rainfall events degrade public waterbodies. Because combined sewer overflows (CSOs) especially affect public waterbodies, necessary measures must be taken for CSOs. Therefore, this study treated CSOs using the ultra-rapid coagulation (URC) process. More than 50% of the study site was comprised of an industrial area, followed by forest, farmland and residential areas at 21.3, 2.6, and 23.5%, respectively. The 30,000 ton capacity URC process was used to treat CSOs generated from the catchment. Monitoring was conducted over 8 rainfall events, and the samples were analyzed for pollutant parameters such as total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD_{cr}), total nitrogen (TN), total phosphorus (TP), and heavy metals. At the beginning of the rainfall, the first flash effect was observed, but was not observed 20 min later. The concentration of TSS and BOD increased as the rainfall intensity became stronger in the middle stage of the rainfall. The treatment efficiency of the pollutants by the URC process was analyzed as TSS 94.4%, BOD 70.8%, COD_{cr} 77.6%, TN 36.1%, and TP 83.5%. These treatment efficiencies were higher than those of other nonpoint pollution control facilities. Meanwhile, the removed particle size ranged from 0.1 to 10 μm or from 80 to 300μm.

Keywords: Ultra rapid coagulation (URC); Coagulation; Weighted coagulant additives (WCAs); CSOs; Alum

*Corresponding author.

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1. Introduction

Pollutants that flow into public waterbodies are usually classified as point pollution sources and nonpoint pollution sources. A point pollution source is a pollutant source generated from fixed area such as domestic sewage and factory waste. On the other hand, a nonpoint pollution source discharged with runoff generated during rainfall is composed of dust, garbage, fertilizer, and agricultural chemicals sprayed at farmlands, and residues of animals and plants [1].

The Korean Ministry of Environment (MOE) promotes total maximum daily loads at four major rivers. The government has tried to improve water quality by the management of point pollution sources including an extension of livestock wastewater treatment plant (WWTP), an extension and improvement of sewage treatment plant. However, despite these efforts and investment, water quality has not been improved due to the huge affect of nonpoint pollution sources generated without management in rainfall.

According to the four major river water management comprehensive countermeasures, the ratio of nonpoint pollution source of total waterbody pollution source ranges from 22 to 37%. Furthermore, the Korean MOE predicts that the level of contribution for the deterioration of water quality will increase up to 65 to 70%. Therefore, based on above results, it is likely that the quality of public water system will be no more improved under current water treatment system. As alternatives for water management, the government has been actively pushing ahead with studies and establishing countermeasure.

Sewer systems at urban areas, meanwhile, are classified as combined sewer system (CSS) and separated sewer system (SSS). In the latter, the pollutant load discharged to the river during raining is small due to discharging through the SSS after runoff and the sewage is separated. CSS, however, discharges a lot of pollutants into the river because the sediments settled during the dry season are washed out by runoff generated under the rainfall. According to the results of the study about combined sewer overflows (CSOs), the concentration of CSOs is affected by rainfall duration, rainfall intensity, existing land use, and development of catchment surface [2–4].

The pollutant load of CSOs is estimated at about two times the pollutant amount generated from nonpoint pollution sources. It also reported that the fluctuation range of CSOs water quality during the dry season is 2–3 times and the fluctuation range of water quality during rainfall is increased more than 10 fold compared with the usual [5,6].

A report of the US Environmental Protection Agency indicated that the discharge of CSOs into public waterbodies must be controlled for successful water management because they contain many kinds of pollutant including organic matter, bacteria, nutritive substance, turbidity, total suspended solids (TSS), and toxic substance [7]. The measures for CSOs in sewage facility standards published by the Korean MOE are proposed as follows: storm water tank, swirl regulator, filter screen, rainwater infiltration facility, and real-time control

Polymer flocculants, such as polyaluminum chloride and polyferric sulfate, are widely experimented in water treatment [8]. Although many coagulants are used, until now, very limited information on coagulant addition, especially optimization of coagulant addition and feasibility of their application, has been obtained so far [9]. For the rapid treatment of a large amount of wastewater, meanwhile, Europe has developed processes such as ACTIFLO [10] and DENSADEG [11,12]. These processes simultaneously inject a coagulant and Weighted Coagulation Additives (WCAs) and thereby improve the precipitation velocity. However, the WCAs used in this process have weaknesses that cause corrosion of pump and pipes by recycling themselves in the system. In order to overcome these problems, ultra rapid coagulation (URC) process was used for treating CSOs in this study. URC is a process in which sludge is recycled to provide the core for coagulation and the settle velocity is maximized by using an inclination plate settler. This study analyzes the treatment efficiency and the advantage obtained by injecting the coagulations and WCAs. The applicability of the URC process in the treatment of CSOs is studied by examining the particle size treated by the URC process.

2. Materials and methods

2.1. Study area

The catchment of Dae-Myung (DM) river in Daegu, Korea, is used as the study area to investigate the runoff characteristics of CSOs and applicability to treat CSOs by URC process. DM river, which has a catchment area of about 998 ha, is used as a sewer system that carries to a sewage treatment plant after intercepting for sewage and runoff from its basin. Table 1 shows the land use type rate of DM river catchment. More than 50% of the study site is occupied by industrial area followed by forest, farmland, and residential areas at 21.3, 2.6, and 23.5%, respectively. A map of the catchment is shown in Fig. 1. Upstream of the river basin is used for residential and

Table 1
Land use type rate of DM river catchment

	Industrial	Forest	Farmland	Residential
Land-use type rate (%)	52.6	21.3	2.6	23.5

commercial areas. In contrast, downstream is used for industrial area.

S WWTP, with a capacity of 52,000 m^3/day at the lower of DM river, treats the sewage generated from the catchment. Otherwise, during significant rainfall events, the sewer flow exceeds the hydraulic capacity of the CSS and the WWTP. The exceeded sewer flow is treated by the URC process located within WWTP.

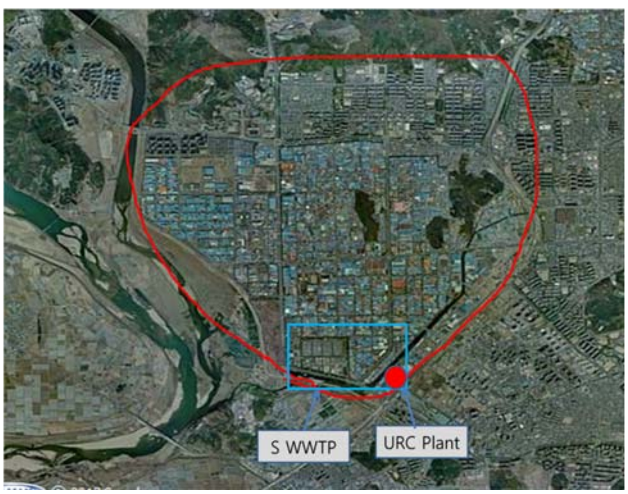

Fig. 1. Map of the study area.

2.2. URC process

The URC process in this study was applied to treat CSOs generated during a significant storm event (Fig. 2). The URC process has the following characteristics: injection of WCAs, return of the settled sludge, and installation of multislope panel settling tank. WCAs, which are mixed with powdered glass, bentonite, and diatomite in the ratio of one to one to two, reduce the response time by removing the bigger flocs. After some of the settled sludge in settling tank is returned to the rapid-mixing tank, it is used again as a core for coagulation of the pollutants. Returned sludge may have a role to improve the treatment efficiency by keeping solids in the rapid mixing tank at high concentration.

Meanwhile, the capacity of the URC process is 30,000 ton and the treatment stage is comprised of a grit chamber, retention basin, rapid mixing tank, mixing tank, slow mixing tank, and settling tank (Table 2).

Pollutants in the source water in the rapid mixing tank are formed as the first coagulation with injected coagulant and returned sludge. After the pollutants are agglomerated with a coagulant in the rapid mixing tank, it moves to a mixing tank with injected WCAs to instigate flocculation. After the pollutants are agglomerated with a coagulant in the rapid mixing tank, they are moved to a mixing tank with injected WCAs to induce flocculation. The flocs made in the mixing tank are moved to a slow mixing tank. Flocculation is also combined with particles by anionic polymer injected in the slow mixing tank. The well-settled flocs arriving in the settling tank are quickly deposited and some of them engage in cohesion process again after being returned to the rapid mixing tank, where even fine particles are combined by anionic polymer injected in

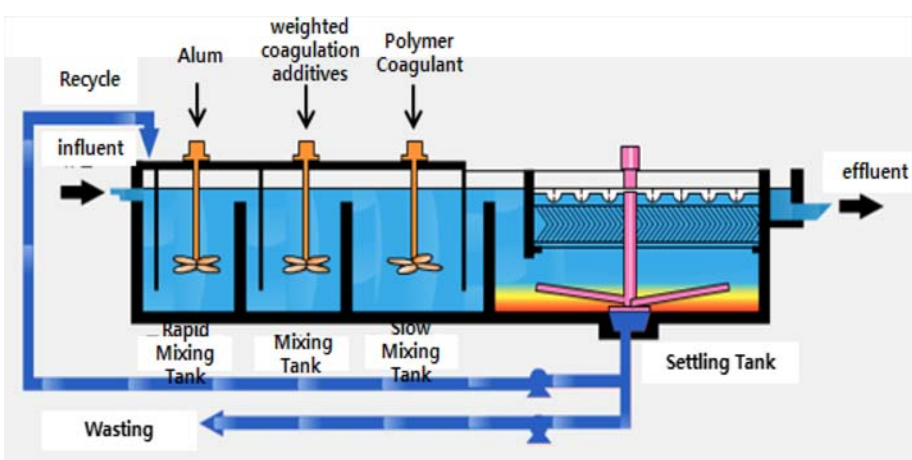

Fig. 2. Schematic process diagram of the URC system.

Table 2
Capacity and size of the URC process

Parameter	Grit chamber	Retention basin	Rapid mixing tank	Mixing tank	Slow mixing tank	Settling tank
Capacity (m^3)	280.08	24,196	115	205	293	1,094
Size (W (m) × L (m) × H (m))	4.5 × 16.0 × 3.89	52 × 99 × 5	3.9 × 4.2 × 7.5	3.9 × 4.2 × 7.5	3.3 × 12.5 × 7.5	12.5 × 12.5 × 7.5
Hydraulic retention Time (HRT)	–	24 hr	5.5 min	9.8 min	14 min	52.5 min

the slow mixing tank. The well-settled flocs in the settling tank are settled rapidly and a portion of the flocs undergo further coagulation after being returned. Alum in liquid phase [($Al_2(SO_4)_3$, $18H_2O$)] and an anionic polymer of polyacrylamide, generally used as a good processing additive, were used as the coagulant and flocculent, respectively. No NaOH was added because the pH of the source water in the presurvey was already within the 7 to 8 range.

2.3. Method of monitoring and the amount of coagulant in the URC process

Monitoring of the survey concentration range of CSOs generated from CSS and the suitability of the URC process for the treatment of CSOs was conducted at the URC process located in S WWTP in Daegu, Korea. Monitoring was conducted for 8 events from March 2010 to July 2011. Table 3 shows a summary of the events. The sampling for analysis was selected from the influent, that is, the source water into the grit chamber generated from the catchment and final effluent discharged through the multi-slope panel settling tank. It took 3 h for the influent sampling, as it usually takes about 3 h to fill with influent up to 30,000 m^3, which is the treatment capacity of the URC process. The sampling of the inflow were conducted in each organized sampling time (5, 5, 10, 10, 15, 15, 20, 20, 20, 30, 30 min) for the examination of the concentration change according to the passage of time at the beginning of the generating CSOs. The effluence from the multi-slope panel settling tank was discharged for 24 h, and the effluences were sampled at 2 h intervals. Table 4 shows the treated flow, generated sludge, and the amount of coagulant used.

Table 3
Summary of events

Event no.	Date (mm/dd/yy)	ADD (days)	Total rainfall (mm)	Runoff duration (hr)	Avg. rainfall intensity (mm/hr)
E-1	07/16/10	3	59.5	8	8.7
E-2	11/11/10	10	1.5	4.5	0.33
E-3	12/13/10	25	1.0	0.5	2
E-4	06/23/11	2	28.5	7	1.8
E-5	07/04/11	2	28.5	18	1.58
E-6	07/07/11	3	15	19	0.79
E-7	07/11/11	2	165.5	44	3.76
E-8	10/17/11	5	4.5	7	0.64

The treated flows ranged from 16,803 to 23,000 m^3 and the amount of alum used ranged from 2,420 to 3,090 kg. Water quality parameters such as chemical oxygen demand (COD_{cr}), TSS, total nitrogen (TN), total phosphorus (TP), and biochemical oxygen demand (BOD) were analyzed in accordance with Standard Methods. Heavy metals such as Cadmium (Cd), Chromium (Cr^{3+}, Cr^{6+}), Plumbum (Pb), Copper (Cu), and Mercury (Hg) were also analyzed.

2.4. Analysis contents

The outflow trend analysis of the CSOs concentration was conducted to investigate the first flash effect of CSOs during rainfall. Large amounts of CSOs occurred during the rainfall are difficult to treat in social/economic aspects of this study area. Therefore, a reasonable volume of CSOs must be treated. The outflow trend analysis of the CSOs concentration was very useful for determining the treatment volume of CSOs. Otherwise, this study determined the pollutant event mean concentration (EMC) of inflow and outflow and the treatment efficiency to decide the applicability of the URC process for CSOs treatment. EMC is calculated by the following expression:

$$\text{EMC (mg/L)} = \frac{\text{Discharged mass during an event}}{\text{Discharged volume}} = \frac{\int_0^T C(t) \times Q_{\text{TRu}}(t)\,\mathrm{d}t}{\int_0^T Q_{\text{TRu}}^{(t)}\,\mathrm{d}t} \tag{1}$$

where, $C(t)$ and $Q_{\text{TRu}}(t)$ are the pollutant concentration and runoff ratio, respectively, about t, which is the rainfall duration. Removal efficiency calculations were based on the following mass balance:

Table 4
Volume of treated flow and amounts of coagulation used in the URC process

Event no.	Flow (m^3/d)	Alum (kg)	Polymer (kg)	WCAs (kg)	Antifoaming agent (kg)	Amounts of sludge (m^3)
E-1	21,949	2,420	22	110	0	233
E-2	16,903	2,890	20	155	0	201
E-3	19,803	2,880	22	165	40	293
E-4	19,278	3,090	20	165	40	147
E-5	23,000	3,030	25	60	60	154
E-6	21,796	3,008	25	0	60	152
E-7	21,164	2,980	25	0	60	135
E-8	19,684	2,505	20	0	60	125

$$\eta = \left(1 - \frac{C_e}{C_i}\right) \times 100 \quad (2)$$

where, C_i and C_e are, respectively, the influent EMC and effluent EMC concentration in mg/L. Particle analysis of the inflow and outflow was conducted to investigate the particle size removed by the coagulation process.

3. Results and discussion

3.1. Runoff characteristics of CSOs

Industrial areas accumulate oil material, including oil and antifreeze and pollutants such as BOD, COD_{cr}, and TN during dry weather and discharge them during rainfall. In general, the concentrations and types of pollutant in runoff from industrial areas are higher than those of residential and commercial areas [13]. Fig. 1 shows the concentration change of the pollutants in CSOs. As shown in Fig. 1 involving concentration change of pollutants, first flash effect was identified in most of rainfall event. After the first flash effect, the runoff concentration of the pollutants was gradually reduced. However, it was analyzed that the concentration of TSS and BOD increased as the rainfall intensity became stronger in the middle stage of the rainfall. The rainfall intensity was attributed to the runoff concentration of the pollutants (Fig. 3).

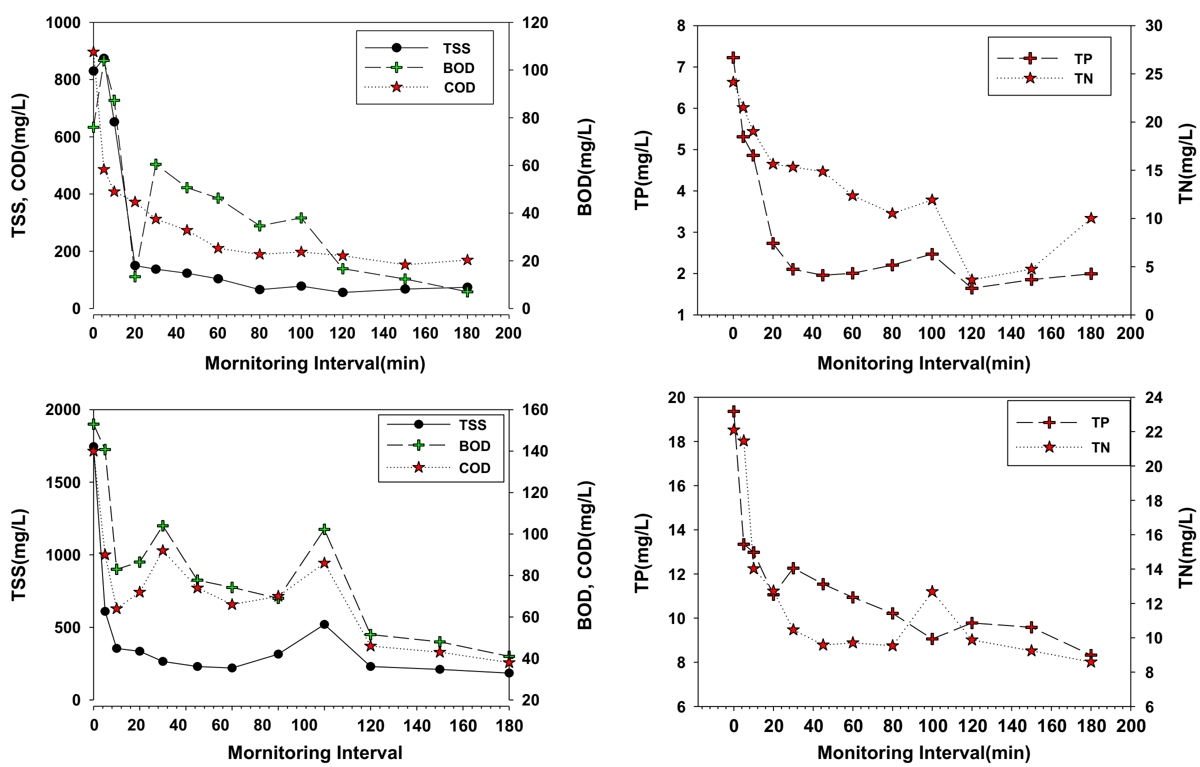

Fig. 3. Pollutant graphs for two events (E-5, E-8).

After the rainfall started, the first flush effect was finished in 30 min. This first flash effect was considered an important reference for determining the treatment amount of CSOs.

3.2. Statistical analysis of the pollutant concentrations in CSOs

Statistical analysis of the pollutant concentration was conducted to analyze the outflow range of pollutants in CSOs generated during rainfall. The COD_{cr}, TN, and TP concentrations ranged from 7 to 70.8 mg/L, 1.01 to 2.7 mg/L and 0.59 to 18.59 mg/L, respectively. These pollutant parameters exhibited large concentration ranges, which revealed the high uncertainty in the nonpoint source. This uncertainty was attributed to a variety of causes such as rainfall intensity, catchment area, catchment slope, sewer flow, impermeable ratio, and monitoring method, which reveals the necessity of long-term monitoring. The arithmetical mean concentrations of TSS, BOD, COD_{cr}, TN, and TP were analyzed as 232.9, 70.8, 197.7, 2.7, and 18.5 mg/L, respectively. As a result of the analysis of the 95% conference interval for each pollutant, the minimum and maximum TSS concentration ranged from 189.6 to 276.1 mg/L.

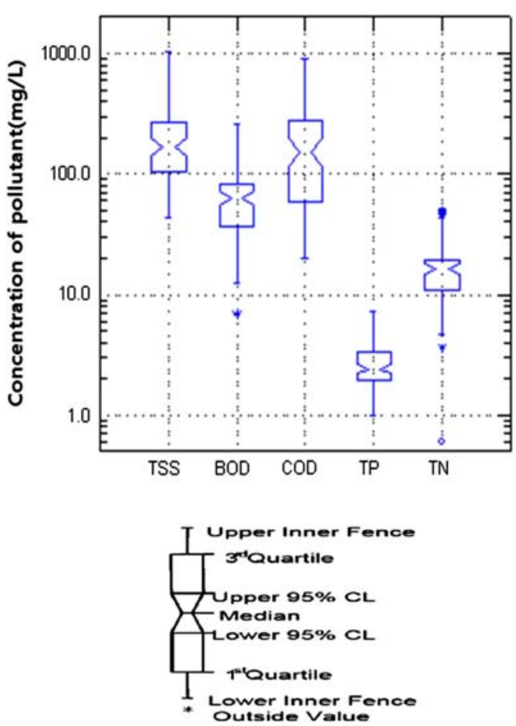

Fig. 4. Notched box plot for pollutant concentration.

The BOD concentrations ranged from 60.6 to 80.9 mg/L. The COD_{cr} concentrations ranged from 161.4 to 233.9 mg/L. The minimum and maximum concentrations of TP and TN ranged from 2.4 to 2.9 mg/L and from 16.1 to 20.8 mg/L, respectively (Fig. 4).

3.3. EMC and treatment efficiency

In the initial stage of a rainfall event, the discharge of any CSOs containing a high concentration of pollutants without any treatment processing generates problems including contamination of water, stench, and eutrophication. Therefore, CSOs were treated in this study by using the URC process. The EMC of the inflow and outflow and the treatment efficiency of the URC process are analyzed and the results shown in Table 5.

Each pollutant EMC of inflow was measured as follows: 91.5–560.2 TSS mg/L, 31.2–156.1 BOD mg/L, 39.77–316.42 COD_{cr} mg/L, 9.5–16.58 TN mg/L, and 1.46–6.45 TP mg/L. Each pollutant EMC of outflow was measured as follows: 4.0–21.4 TSS mg/L, 5.8–19.9 BOD mg/L, 9.5–29.3 COD_{cr} mg/L, 6.1–9.3 TN mg/L, and 0.3–1.8 TP mg/L.

The average treatment efficiency of TSS was 94.6%. BOD, COD_{cr}, TN, and TP were 80.7, 87.3, 41.4, and 77.6%, respectively. This demonstrated that the treatment efficiency of contaminant in E-6 and E-7 without injection of WCAs was similar to the result of events with injected WCAs. According to Park et al., WCAs are used as a seed to form large flocs in a mixing tank [14].

Therefore, it is effective in forming well-grown flocs. Kawamura reported that the particles can effectively cohere in a short time because of the increased chance to collide with larger sized pollutant particles by using WCAs [15]. WCAs were considered to have more effect on the processing speed than the treatment efficiency, compared with previous results that did not use WCAs.

However, heavy metals were not detected in most events. In general, it is known that high concentration of heavy metals are detected in runoff from industrial complexes. Although industrial areas in this study occupied more than half of the drainage area, heavy metals such as Pb, Cu, Cr, Cd, and Zn were not detected at meaningful levels (Table 6). The reason for why heavy metal was not detected in samples is likely that the heavy metal was diluted by an amount of rainfall runoff and sewage generated from wide catchment area.

Table 5
Concentration of EMC and treatment efficiency of inflow and outflow in the events

Event no.	Inflow/outflow	TSS (mg/L)	BOD (mg/L)	COD_{cr} (mg/L)	TN (mg/L)	TP (mg/L)
E-1	Inflow	132.8	31.2	229.6	9.8	2.2
	Outflow	14.6	12.6	17.9	7.9	0.8
	Treat. effi.	89.0	59.6	92.2	18.9	61.1
E-2	Inflow	87.1	34.9	47.8	22.2	1.7
	Outflow	16.2	15.6	22.5	20.6	0.4
	Treat. effi.	81.3	55.1	52.9	37.2	76.5
E-3	Inflow	315.3	43.9	78.9	16.2	1.8
	Outflow	19.5	18.9	29.3	11.9	0.6
	Treat. effi.	93.8	56.9	62.8	26.1	63.6
E-4	Inflow	364.3	47.4	68.9	13.7	6.9
	Outflow	8.8	12.2	15.9	7.4	1.4
	Treat. effi.	97.6	74.3	76.8	45.5	79.1
E-5	Inflow	281.6	66.7	73.6	21.1	11.6
	Outflow	15.9	13.9	19.2	9.9	1.5
	Treat. effi.	94.3	79.1	73.8	52.9	86.6
E-6	Inflow	321.3	39.3	63.1	10.8	10.3
	Outflow	8.4	8.4	12.4	4.9	1.2
	Treat. effi.	97.4	78.5	80.3	54.5	87.8
E-7	Inflow	170.5	24.0	26.7	14.6	6.5
	Outflow	3.1	3.4	5.6	5.1	1.31
	Treat. effi.	98.2	85.9	78.9	64.7	79.8
E-8	Inflow	149.0	34.6	46.3	19.1	13.2
	Outflow	15.1	8.7	18.8	13.6	1.4
	Treat. effi.	89.8	74.6	59.3	29.1	89.2
Aver.	Inflow	227.7	40.2	79.3	15.9	6.8
	Outflow	12.7	11.7	17.7	10.2	1.1
	Treat. effi.	94.4	70.8	77.6	36.1	83.5

Table 6
EMC concentration of heavy metals in CSOs

Event	Inflow/outflow	Pb (mg/L)	Cu (mg/L)	Cr^{3+} (mg/L)	Cr^{6+} (mg/L)	Cd (mg/L)	Hg (mg/L)	n-H (mg/L)
E-1	Inflow	ND	ND	ND	ND	ND	ND	ND
	Outflow	ND	ND	ND	ND	ND	ND	ND
E-2	Inflow	ND	ND	ND	ND	ND	ND	ND
	Outflow	ND	0.01	0.003	ND	ND	ND	ND
E-3	Inflow	ND	0.01	0.005	ND	ND	ND	ND
	Outflow	ND	ND	ND	ND	ND	ND	ND
E-4	Inflow	2	4	ND	ND	2	ND	ND
	Outflow	ND	ND	ND	ND	ND	ND	ND
E-5	Inflow	0.24	0.1	ND	ND	ND	ND	ND
	Outflow	ND	ND	ND	ND	ND	ND	ND
E-6	Inflow	1.4	0.56	ND	ND	ND	ND	ND
	Outflow	0	ND	ND	ND	ND	ND	ND
E-7	Inflow	0.78	0.37	ND	ND	ND	ND	ND
	Outflow	0	ND	ND	ND	ND	ND	ND
E-8	Inflow	3.4	3.3	ND	ND	ND	ND	ND
	Outflow	0.33	0.16	ND	ND	ND	ND	ND

3.4. Analysis of particle size

To survey the efficiency of TSS removal, which is the major purpose of nonpoint pollution control facilities, particle size analysis of the inflow and outflow into the URC process was conducted. The results of particle size analysis are shown in Figs. 5 and 6.

As shown in Fig. 5, the particle size distribution exhibited a normal curve. The most common particle size was 10–300 μm in the inflow and 30 μm in the outflow. This indicated that the particle sizes of 80–300 μm and 0.1–10 μm were mostly removed, probably because most of the 80–300 μm-sized particles were removed by gravity settling in the grit chamber. On the other hand, the small particles sized 0.1–10 μm were treated by using a coagulation process using cohesive agents due to the difficulties in ensuring precipitation in a short time. These particle size analysis results will be useful to understand the characteristics of colloidal material removal. Figs. 5 and 6 compare the distribution of particle size between the inflow and outflow. However, it was not possible to compare the amount of removed particles in constant value.

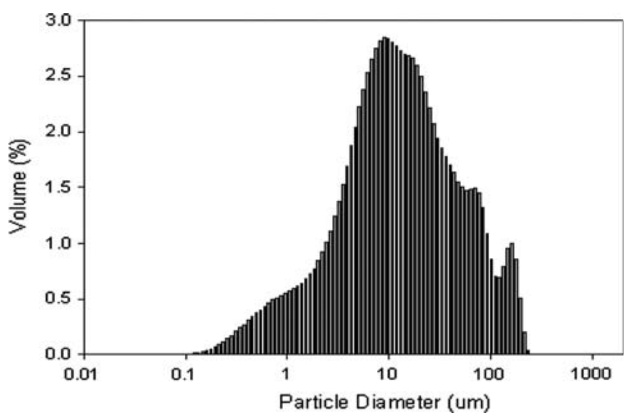

Fig. 5. Distribution of particle size in the inflow (16 July 2010).

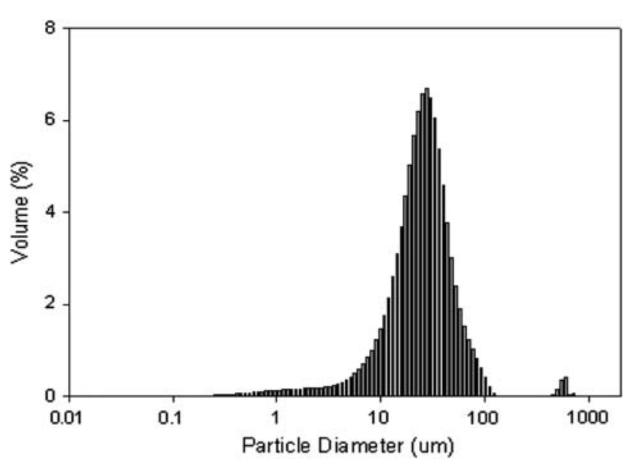

Fig. 6. Distribution of particle size in the outflow (16 July 2010).

4. Conclusions

To treat CSOs generated during rainfall events, the URC process was applied in this study and the following result were obtained.

(1) The graph of the outflow concentration of CSOs generated from CSS revealed that in the initial stage of the rainfall event, the pollutants in the runoff had a high concentration due to the first flash effect. However, within 20–30 min after the finish of the first flash effect, the concentrations of the pollutants decreased. With increasing rainfall intensity, the concentrations of TSS and BOD increased again. However, the concentrations of TN and TP were analyzed to continuously decrease regardless of the rainfall intensity.
(2) From the statistical analysis of the pollutants, the 95% confidence interval of each pollutant ranged as follows: 189.6–276.1 mg/L for TSS, 60.6–80.9 mg/L for BOD, 161.4–233.9 mg/L for COD_{cr}, 2.4–2.9 mg/L for TP, and 16.1–20.8 mg/L for TN.
(3) The mean efficiency removal of the URC process was high for most pollutant parameters. These removal efficiencies were considered to be higher than those for other nonpoint pollutant control facilities.
(4) From the analysis results of the particle size of the inflow and outflow in the URC process, the most common particle size was 10–300 μm in the inflow and 30 μm in the outflow, which indicated that most of the particles sized 80–300 μm and 0.1–10 μm were removed.

In conclusion, the pollutant concentrations in the effluence from CSS exhibited large variations in each rainfall event. Long-term monitoring should be conducted to verify the runoff characteristics of pollutants in CSOs during rainfall. The URC process exhibited high treatment efficiency and the capability of removing even fine particles. These findings demonstrated the potential of applying the URC process to the treatment of CSOs.

However, further research will have to be conducted to investigate the economic feasibility of the URC process.

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