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PREDICTION OF COMBINED SEWER OVERFLOWS CHARACTERIZED BY RUNOFF

Jeongmi Seo*, Yongkyun Cho†, Myongjin Yu*, Seoungkoo Ahn*, Hyunook Kim*†**

*Department of Environmental Engineering, University of Seoul
**Department of Environmental Engineering, Hanseo University
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Abstract : Pollution loading of Combined Sewer Overflows (CSOs) is frequently over the capacity of a wastewater treatment plant (WWTP) receiving the water. The objectives of this study are to investigate water quality of CSOs in Anmyun-ueup, Tean province and to apply Storm Water Management Model to predict flow rate and water quality of the CSOs. The capacity of a local WWTP was also estimated according to rainfall duration and intensity. Eleven water quality parameters were analyzed to characterize overflows. SWMM model was applied to predict the flow rate and pollutant load of CSOs during rain event. Overall, profile of the flow and pollutant load predicted by the model well followed the observed data. Based on model prediction and observed data, CSOs frequently occurs in the study area, even with light precipitation or short rainfall duration. Model analysis also indicated that the local WWTP's capacity was short to cover the CSOs.

Key Words : CSOs, SWMM, WWTP, runoff, prediction

INTRODUCTION

Combined Sewer Systems (CSSs) are for carrying both sanitary sewage (consisting of domestic, commercial, and industrial wastewater) and storm water (surface drainage from rainfall or snowmelt) in a single sewer to a wastewater treatment plant (WWTP). During the dry days, only domestic, commercial, and industrial wastewater flows to a WWTP through CSSs. During rainfall, however, both the wastewater and runoff flow into the CSS or WWTP; frequently with heavy rainfall, the total flow exceeds the CSS and the WWTP. Overflow from the CSS directly flows into surface water body, such as lakes, rivers, estuaries, or coast.[1)]

Normally, during the initial period of stormwater runoff, pollutant's level is substantially higher. This is called first flush phenomenon; during the first flush, a large quantity of pollutants get into water bodies.[2~4)] This type of contamination events is climate-dependent and is frequently occurring, especially in high-rainfall areas.[5)] Typical pollutants found in CSOs include suspended solids, nutrients, biochemical oxygen demand (BOD), pathogenic organisms, and trace metals. The characterization of CSOs is desirable for a better water quality management in an area where CSOs are often occurring.[6)]

Storm water models are frequently used to predict non-point source pollution and to assess the effect of urban development on water resources in advance. Various storm water models have been developed to describe or predict the water quality of runoff in urban areas. Among

† Corresponding author
Yongkyun Cho; E-mail: enpia1@hanseo.ac.kr
TEL: +82-41- 660-1433, Fax: +82-41-660-1119
Hyunook Kim; E-mail: h_kim@uos.ac.kr
TEL: +82-2-2210-5624 Fax: +82-2-2210-2245

them, Storm Water Management Modeling (SWMM, Camp Dresser & McKee and Oregon State University) has been accepted as the standard and successfully applied to various cases.[7~9)] An extensive review of previous studies with SWMM can be found elsewhere.[10)]

In this study, water quality of CSOs in Anmyun-ueup, Tean province was investigated and SWMM was applied to predict flow rate and water quality of the CSOs. Specific objectives of the study include:

- Analysis of CSOs's water quality in the study area,
- Prediction of flow rate and water quality of CSOs using the SWMM,
- Capacity evaluation of a local WWTP according to rainfall durations,
- Prediction of rainfall intensity that the local WWTP can cover at different stages of urban development, i.e., year 2002 and year 2016

METHODOLOGY

Model Description

The EPA's SWMM is a comprehensive hydrological and water quality simulation model to describe the dynamics of rainfall-runoff in urban areas, during single and long term rainfall events.[11)] SWMM is comprised of various modules or blocks, each of which simulates different components. Specifically, the RUNOFF block was used in this study for storm water runoff simulations. Hydrological computations in the RUNOFF block are based on the theory of non-linear reservoirs. Time profile of a pollutant is computed based on the kinematical wave theory. The Horton's pervious area infiltration loss equation was used, which the infiltration capacity reduces in an exponential fashion from the initial.

Surface runoff is computed for any rainfall hyetograph in SWMM. Land use type and topography, antecedent moisture conditions, infiltration losses in pervious areas, surface detention, overland flow, channel/pipe flow and constituents carried by runoff into inlets are considered. Important input parameters are the catchment slope, pervious and impervious depression storage, channel and conduit layout, geometry and properties, the Manning's roughness coefficient for both overland and channel flow, and rainfall intensity.

The RUNOFF block can simulate quality of runoff processes within a drainage basin, and the routing of flows and contaminants along storm drain lines, leading to the calculation of a number of inlet hydrographs and pollutographs. There are several options for computing accumulation and wash-off of pollutants in SWMM; in this study, an accumulation method that follows a power build-up relationship was used:

$$L_t = QFACT(3) \cdot DD^{QFACT(2)} \quad (1)$$

Where L_t is a constituent quantity at time t (kg/ha); DD is the preceding dry weather period (days); QFACT(2) is the power or exponent for the build-up parameter (dimensionless); and QFACT(3) is the coefficient for the build-up parameter (kg/ha · $day^{-QFACT(2)}$). Wash-off is the process of erosion and transport of constituents from a catchment surface during the period of runoff. The following relationship was used, which describes wash-off at each time step to be proportional to the runoff rate Qt to a power WASHPO:

$$M_t = RCOFF \cdot QT^{WASHPO} \quad (2)$$

Where M_t is a constituent load washed off at time t (kg/sec); Qt is the catchment runoff rate (m^3/sec); WASHPO is the exponent or power of the wash-off parameter (dimensionless); and RCOFF (kg/sec · $[m^3/sec]^{-WASHPO}$) is the coefficient for the wash-off parameter. Equations (1) and (2) are commonly used equations in SWMM and were the most appropriate to use with the given data.

Model Calibration

Model calibration was performed using the data of flow and water quality of CSOs in the study area: manually varying the parameters (i.e. impervious depression storage, Horton infiltration parameters and pervious depression storage, Manning's n). For SWMM calibration for flow rate of CSOs, the measured and predicted hydrographs were tried to match by adjusting relevant parameters within the default range. The best calibration was determined by calculating the sum of the squared errors (eq. 3) between predicted and measured hydrograph points at a specific time for a given rainfall event.

$$ERR^2 = \min[\sum(y_o - y_p)^2] \qquad (3)$$

where y_o and y_p are observed and predicted quantities, respectively.

SWMM calibration for water quality of CSOs was performed in the same manner with the hydrograph calibaration. Four water quality parameters, namely QFACT(2), QFACT(3), RCOFF and WASHPO, required in SWMM [Equation (1) and (2)], were adjusted to calibrate the model for each pollutant, until the total predicted loadings matched the measured ones.

Field Site

The CSOs located near a local WWTP in Anmyun-ueup, Tean-gun, Korea were modeled in this study. 16 manholes of the sewer near the WWTP were selected and assigned an ID number. This area was divided into various subareas following the delineation based on the location of manholes. Physical characteristics of each subarea and storm drain inlet location were used to create input files defining the drainage network to be used in modeling with SWMM.

The sample was collected at ID number 16 near the treatment plant. Figure 1 shows sampling site and manhole's identification numbers. Sampling location was selected by the following criteria: convenience of equipment installation, maintenance easiness, safety, possibility of continuous flow measurement and easiness of sampling.

The WWTP has capacity of 1500 m^3/day and

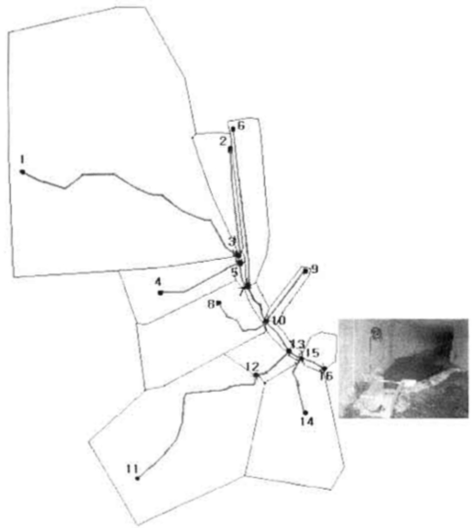

Figure 1. Subarea drawing and sampling investigation site (• : manhole).

has been frequently overflowed.

Data Acquisition

Table 1 and 2 show hydrological input data and water quality parameters used in the SWMM's RUNOFF block. Table 1 exhibits diameter, width, height and length of sewers between two adjacent manholes. Also, it presents runoff coefficients for year 2002 and year 2016 with the consideration of land use and land alteration through urban development. Table 2 presents water quality parameters both for dry weather season (April 5, 2002) and wet weather season (August 22, 2002). Because CSOs's site is situated at the middle position of Seosan and Boryung region, average rainfall intensity data obtained from the observatories in both cities was used.

Flow Measurement and Water Quality Analysis of CSOs Site

Flow rate was measured every 10 minutes using an automatic flow meter (Sigma 920, USA) on 5^{th} and 6^{th} of April and 22^{nd} and 23^{rd} of August. Samples were more frequently collected for the first one hour to observe first flushing. To characterize the water quality, the following parameters were analyzed; BOD_5,

Table 1. Hydrological data used in SWMM's RUNOFF block

Man-hole ID	Circle PD (mm)	Square PW (m)	Square PH (m)	Length (m)	Manning's n	Elevation SP (m)	Elevation EP (m)	Slope (%)	2002 Area (ha)	2002 RC	2016 Area (ha)	2016 RC
1~3	-	2.3	1.5	478.0	0.013	24.5	7.4	3.577	18.293	0.41	15.895	0.48
2~3	600	-	-	221.6	0.013	22.2	8.0	6.408	2.300	0.65	2.300	0.75
3~5	-	2.3	1.5	10.0	0.013	7.4	7.3	1.000	0.015	0.80	0.015	0.80
4~5	-	1.0	0.6	167.2	0.013	22.5	8.4	8.433	3.071	0.47	3.070	0.56
5~7	-	2.3	1.5	30.0	0.013	7.3	5.8	5.000	0.116	0.80	0.116	0.80
6~7	600	-	-	333.3	0.013	23.6	7.0	4.980	2.575	0.64	2.580	0.80
7~10	-	1.5	1.5	90.2	0.013	5.8	5.0	0.887	0.250	0.80	0.250	0.80
8~10	600	-	-	200.1	0.013	11.3	5.4	2.949	4.824	0.55	4.940	0.60
9~10	600	-	-	118.4	0.013	15.6	5.9	8.193	0.564	0.35	1.692	0.80
10~13	-	2.5	2.0	70.0	0.013	5.0	4.5	0.714	0.181	0.80	1.461	0.80
11~12	800	-	-	296.2	0.013	25.0	8.1	5.706	6.488	0.51	6.663	0.59
12~13	-	1.0	1.0	82.9	0.013	8.1	6.0	2.533	2.416	0.69	2.416	0.80
13~15	-	2.5	2.0	30.0	0.013	4.5	4.3	0.667	0.058	0.78	0.247	0.80
14~15	-	1.5	0.7	125.0	0.013	17.1	5.3	9.440	4.969	0.76	1.303	0.80
15~16	-	2.5	2.0	50.0	0.013	4.3	4.0	0.600	0.808	0.56	1.090	0.69

PD: pipe diameter, PW: pipe width, PH: pipe hight, SP: starting point, EP: ending point, AA: accumulation area,
RC: runoff coefficient (land use RC *land use area / total land area),
Land use RC; residence: 0.8, commerce: 0.8, village: 0.65, green zone & others: 0.35
Data from geographic information map of Anmyun-ueup, Tean-gun, Korea

Table 2. Water quality parameter used in SWMM's RUNOFF block

All land uses	DD	QFACT(2)	QFACT(3)	WASHPO	RCOFF
Dry weather (April 5, 2002)	6	0	0	2	1
Wet weather (August 22, 2002)	1	0	0	1	1

chemical oxygen demand (COD_{Mn}; by Mn-method, COD_{Cr}; by Cr-method), total nitrogen (TN), total phosphorus (TP), suspended solids (SS), total solids (TS), volatile solids (VS), settling solid (setS), heterotrophic plate count (HPC), coliforms (Coli). Among the parameters, TS, SS, BOD_5, COD_{Mn}, TN and TP load were compared with model prediction. The experimental procedures for analyzing the parameters follow the Korean Standard Method.[12)]

RESULTS & DISCUSSION

Prediction of Flow and Water Quality

The flow rates at each CSOs site on a raining day during dry and wet weather seasons were modeled(Figure 2).

In general, the model prediction reasonably followed real data. The correlation between model prediction and the observed flow rate was above 0.95 ($p<0.001$) in both dry and wet season cases. However, it underestimated the CSO flow rate, when there was high precipitation; at around 8:00 am on April 5 and at around 5:00 pm on August 22. On the raining day in the dry season, the flow rate of the CSOs went up 0.37 m^3/sec, while the model predicted it 0.47 m^3/sec with the rainfall of 7 mm/hr. On the raining day in the wet season, 1.3 m^3/sec of CSO flow rate was observed with rainfall of 9 mm/hr. However, model predicted the flow rate would go up to 0.80 m^3/sec with the rainfall.

Water quality data of CSOs which occurred on the sampling days are provided in Table 3. Also, observed pollution loading is presented in Figure 3 to 5 along with correlation factors and compared with the model prediction. The pollu-

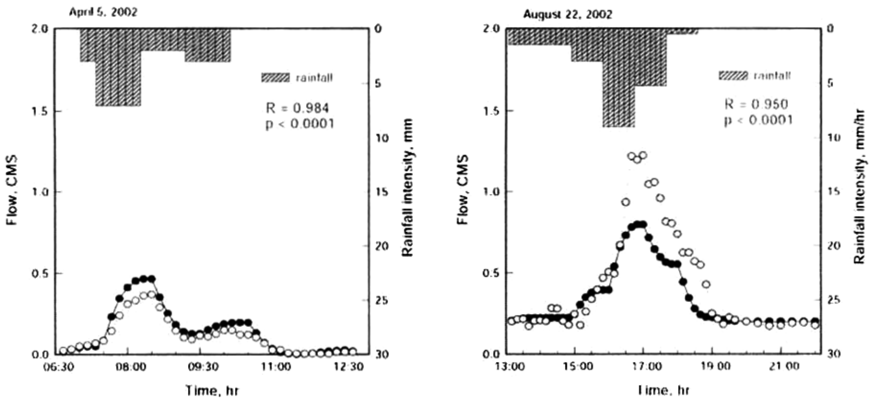

Figure 2. Comparison of observed flow, predicted flow and rainfall intensity at CSOs site (●: Predicted, ○: Observed).

Table 3. Water quality analysis data of CSOs site

Item	April 5, 2002					August 22, 2002									
	6:38	7:00	8:00	10:00	12:25	13:10	13:15	13:27	13:37	14:00	15:00	15:50	18:00	20:00	22:00
BOD_5	52	34	129	30	66	28	30	30	30	12	14	24	22	26	34
COD_{Mn}	28	26	72	20	24	36	34	34	46	28	26	32	24	32	38
COD_{Cr}	124	97	508	100	115	60	67	54	76	36	41	41	38	52	41
SS	70	172	1070	700	58	146	326	178	150	6	12	12	26	14	14
TN	8.2	7.7	7.3	4.8	5.3	5.8	5.8	5.7	7.0	5.4	5.2	4.6	4.7	4.9	4.3
TP	1.3	1.0	4.4	1.2	1.3	0.4	0.4	0.4	0.4	0.4	0.3	0.2	0.1	0.2	0.1
TS	396	385	1335	480	792.5	NA	778	676	NA	420	390	380	NA	400	410
VS	114	88	355	93	155	NA	138	100	NA	84	92	78	NA	96	106
setS	0.3	1.5	4.5	1.5	0.5	NA	0.3	0.3	NA	0.4	0.4	0.3	NA	0.4	0.4
HPC	800	1100	1900	2400	1000	1100	NA	NA	1900	NA	NA	NA	800	NA	NA
Coli	500	700	1000	1100	700	700	NA	NA	1000	NA	NA	NA	500	NA	NA

tion loading was calculated by multiplication of pollutant concentration to flow.

After an intensive rainfall, pollution loading was significantly increased, showing first flushing phenomenon. Particularly, this phenomenon was prominent during dry weather season. This is because there had been no precipitation for 6 days before the first rain event. During the dry days, pollutants (e.g., clay, sand and organics) settled and remained within sewer pipes and were flushed with the intensive rainfall. Thus, these pollutants had influence on increment of TS, SS, BOD_5, COD_{Mn}, TN and TP loading. In the case of wet weather season, there was a day before the sampling day, so flush phenomenon after intensive rainfall showed only small SS, BOD_5 and TP loading. The overall high pollution loading at this time resulted simply from large precipitation.

As is showed in Figure 3 to 5, there was strong correlation between predicted values and observed values in the case of dry weather season.

Relationship between Rainfall Duration and Amount of Flow to WWTP

The CSOs can easily exceed the capacity of a WWTP and directly flow into a receiving water body, resulting in serious water quality problem. Thus, the CSOs flow rate according to rainfall duration was predicted by SWMM. Based on the model, flow rate exceeds the maximum capacity of a local WWTP in about 20 min after rainfall is started. Rainfall intensity assumed for the

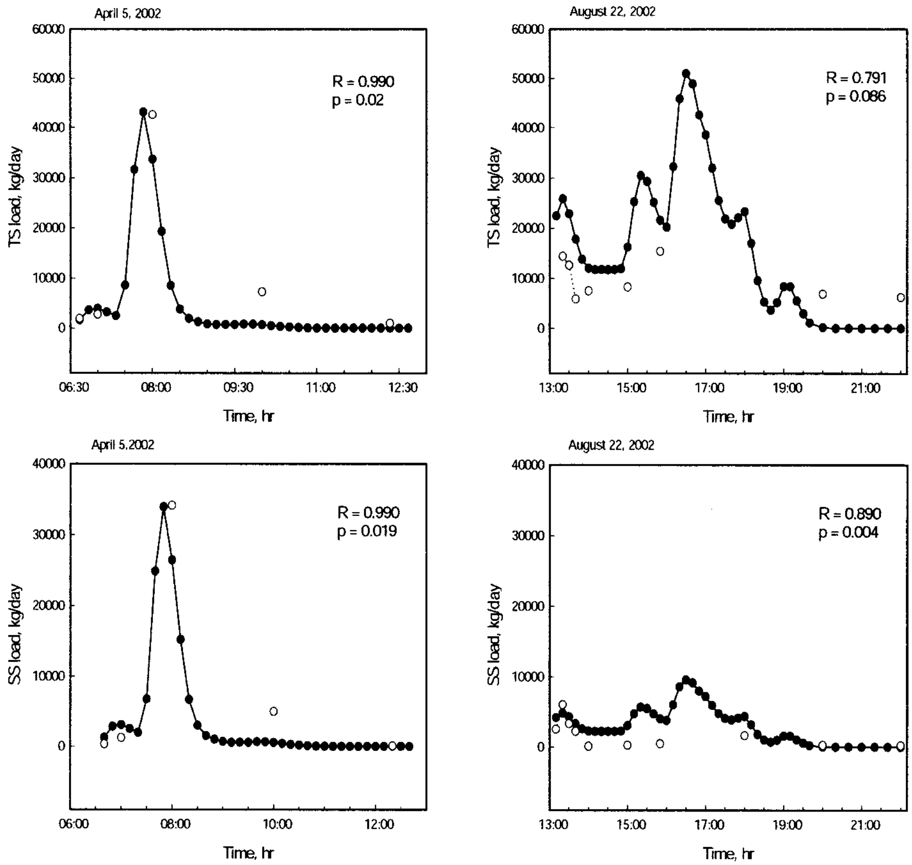

Figure 3. TS and SS loadings predicted by SWMM (●: Predicted, ○: Observed).

model was 2 mm/hr, which is considered as low rainfall intensity. Simulation result from SWMM's RUNOFF block is presented in Figure 6.

The data of year 2002 and year 2016 (Table 1) assuming urban developments were used for prediction of rainfall intensity acceptable in WWTP. The rainfall intensity that the WWTP can cover was simulated in Figure 7. The rainfall duration considered in the model was 1 hour. According to the simulation result, rainfall intensity that the plant can cover will decrease from 1.15 mm/hr in 2002 to 1.07 mm/hr in 2016 because of more urbanization of study area.

Since the plant's capacity cannot cover the flow from the low rainfall intensity, a storm water management plan for the WWTP in the study area should be initiated. It is also desirable to increase the capacity of WWTP to cover the additional CSOs.

CONCLUSION

During precipitation in dry and wet weather seasons, CSOs samples were collected and analyzed to apply SWMM model and to predict flow rate and water quality of CSOs. Predictions by SWMM were compared with the observed values. In addition, capacity of a local WWTP in the study area was evaluated based on the model prediction.

When storm water runoff started with intensive rainfall, high pollution loading was observed both in dry and wet seasons; especially, in the dry season. It is reasonable since more pollutants settled down in sewers during dry days and flushed out with any intensive rain event.

The SWMM model reasonably predicted flow rate and pollution loading caused by CSOs, although it underestimated the flow rate espe-

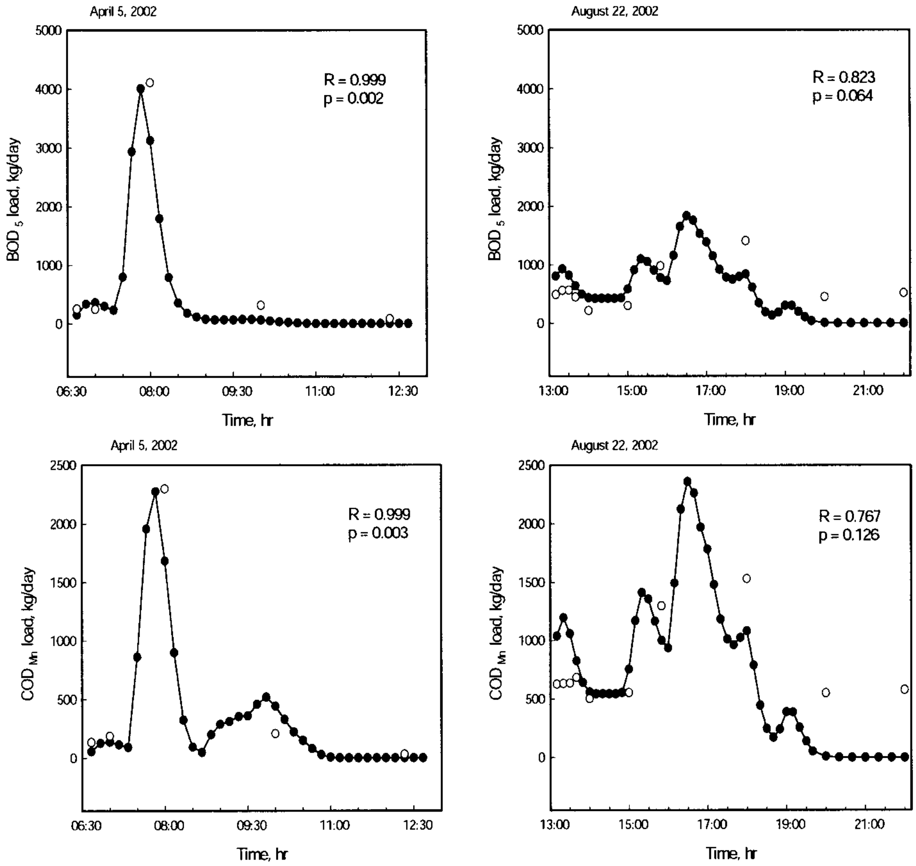

Figure 4. BOD_5 and COD_{Mn} loadings predicted by SWMM (●: Predicted, ○: Observed).

cially during the periods of intensive rainfall. Figure 2~5 showed strong correlation between model prediction and observed values.

Based on observed and predicted flow rate of CSOs, the treatment capacity of the WWTP in the study area can be easily exceeded even with the rainfall intensity of 2 mm/hr. CSOs were predicted to occur in about 20 min after the rainfall is started. The maximum rainfall intensity that the WWTP can cover in year 2002 and in year 2016 was estimated 1.15 mm/hr and 1.07 mm/hr during 1hr rainfall duration, respectively. Therefore, extension of the current WWTP and a new storm water management plan should be made.

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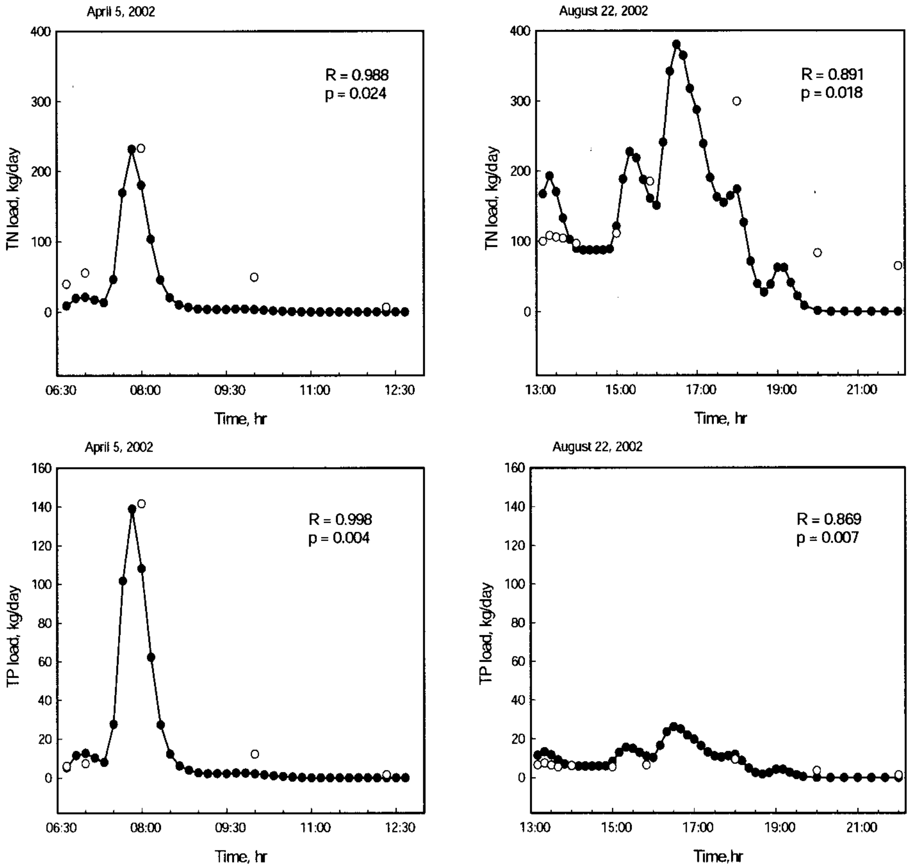

Figure 5. TN and TP loadings predicted by SWMM (●: Predicted, ○: Observed).

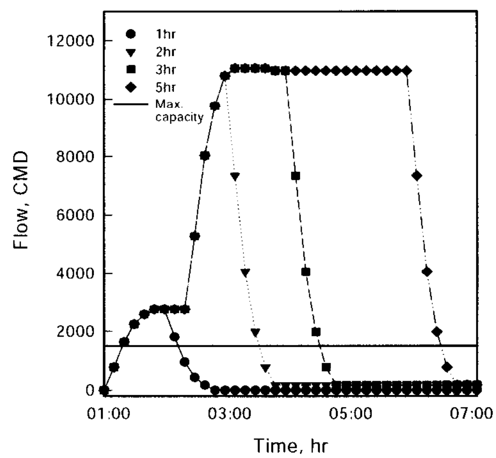

Fig. 6. Flow variation during rainfall period.

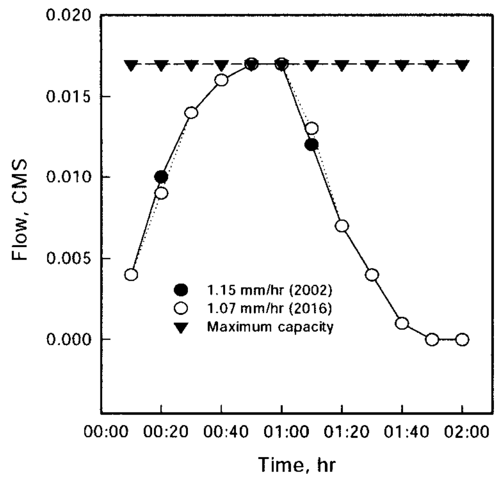

Fig. 7. Prediction of rainfall intensity acceptable to the local WWTP; case of 1hr rainfall duration.

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