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Original Article

Characterization of water quality among direct and delayed wet -weather flows in an urban combined sewer catchment of Thailand

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Abstract

The purpose of this research was to compare five water quality parameters (BOD, TSS, total zinc, TKN, and fecal coliform) in wet-weather flow of a combined sewer catchment against dry-weather flow, while making a distinction between direct and delayed inflow, which has often not been made. Correlations and event mean concentrations (EMCs) were also calculated. A total of 38 samples were collected from Khon Kaen's combined sewer system between March and August 2015. Concentrations in direct inflow of three parameters: total zinc ($\bar{x}$ = 0.24 mg/L, IQR = 0.12-0.34), TSS (240 mg/L, 176-356), and BOD (59.7 mg/L, 42.4-77.8) were higher than delayed inflow ($\bar{x}$ = 0.04 mg/L, 36 mg/L, and 23.7 mg/L, respectively). Concentrations of delayed inflow were similar to or lower than dry-weather flow. Pollutant concentrations for particulate-based pollutants were much higher during the direct inflow phase of rain events compared to the delayed inflow phase. Dissolved-phased nutrients, however, were not different.

Keywords: combined sewer overflow, event mean concentration, stormwater, surface water quality, urban runoff

1. Introduction

Urban runoff, which mobilizes and transports accumulated pollutants from urban impervious surfaces, is an important environmental concern. Urban runoff has been extensively studied across the United States, Europe, China, and South Korea (Barco, Papiri, & Stenstrom, 2008; Behera, Adams, & Li, 2006; Huang *et al.*, 2007; Qin, Tan, Fu, Zhang, & Huang, 2013; Wang, Wei, Huang, Wang, & Maqsood, 2011). In the United States, an extensive database (National Stormwater Quality Database, v. 4.02 [NSQD]) of pollutant event mean concentrations (EMCs) has been compiled from more than 9000 events at over 100 sites across the country (Pitt & Maestre, 2004). Data show that the concentrations of each pollutant vary depending on several factors of the urban catchment, such as its area, land use, vehicle use, and other hydrologic and hydraulic factors (Brezonik & Stadelmann, 2002; Gooré Bi, Monette, & Gasperi, 2015; Mailhot, Talbot, & Lavallée, 2015).

When collected in separate sewer systems and treated, stormwater poses minimal ecological or human health risks. However, in many older or lesser developed cities across the world, untreated stormwater and wastewater is discharged to surface water via combined sewer systems and their combined sewer overflows (CSOs). The discharge from CSOs to receiving surface water bodies contains sediment, oil, hydrocarbons, nutrients, heavy metals, biological oxygen demand (BOD), bacteria and other biological agents (Field *et al.*, 1998). It can have significant effects on the water quality and ecology of surrounding urban waterways, such

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as dramatically higher concentrations of bacteria in surface water bodies (Passerat, Ouattara, Mouchel, Vincent, & Servais, 2011) or reduction in a wide range of aquatic life from suspended solids (Bilotta & Brazier, 2008). The addition of pollutants to urban waterways creates opportunities for human exposure and resulting health risks via fish consumption, bathing, or water consumption (Gaffield, Goo, Richards, & Jackson, 2003).

Nearly all cities in Thailand use combined sewer systems, in which stormwater, domestic wastewater and industrial wastewater are collected into a single sewer system with one or more CSOs allowing discharges greater than the system's capacity to overflow to a local water body. Thai municipal wastewater treatment plants (WWTPs) have an estimated nationwide capacity to treat only 20% of wastewater annually generated (Siripornpipul, 2014; World Bank, 2011), necessitating CSOs. These CSO discharges are not regulated by the Thai Pollution Control Department (PCD), unlike municipal, residential, and industrial effluents. Very little is known about the quantity or quality of urban runoff that is generated and discharged to surface water bodies in Thailand to the authors' knowledge.

Combined sewer systems represent an environmental risk, because concentrations of most pollutants in CSO discharges are higher than in stormwater alone, due primarily to remobilization of sewer deposits (Chebbo, Gromaire, Ahyerre, & Garnaud, 2001). The distribution of contaminant concentrations in dry-weather and wet-weather flow within combined sewer systems has been analyzed, demonstrating that concentrations of particulate and oxygen-consuming matter are higher in wet-weather flow than dry-weather flow (Piro, Carbone, & Sansalone, 2012). However, a distinction has not been made between direct inflow and delayed inflow CSO discharge. Large urban catchments can have significant, diluted flow, known as delayed inflow, for an extended period of time after the conclusion of the rain event due to infiltration, delayed storage and pumping (Metcalf & Eddy *et al.*, 2003). The distinction between direct and delayed inflow has important ramifications for regulators and treatment plant operators. The two wet-weather flow regimes may represent different concerns and contaminant sources, which is important information for optimizing expenditures for treatment.

Therefore, the purpose of this study was to characterize discharge in CSO events and compare concentrations of several pollutant indicators between wet and dry-weather flow, making a distinction between direct and delayed inflow using Khon Kaen municipality's combined sewer system in the Chi-Mun River basin as a study setting. Thus, the study included the following objectives: (1) provide a statistical summary of water quality during CSO events, (2) compare pollutant concentrations from direct-inflow CSO discharge and delayed-inflow CSO discharge against values in untreated wastewater, and (3) evaluate the correlation of concentrations between pollutants. A secondary purpose of this study is to describe the characteristics of CSO discharge and evaluate potential sources, which will help establish guidelines for CSO regulations in Thailand.

2. Methods and Materials

A total of 38 water quality samples were collected from the Khon Kaen municipality combined sewer system between March and August 2015 and were analyzed for five parameters. As well, flow was calculated from water level at a weir using pressure transducers installed in the sewer system from December 2014 to August 2015. The following section presents all methods.

2.1 Description of study catchment

Khon Kaen is located in northeast Thailand within the

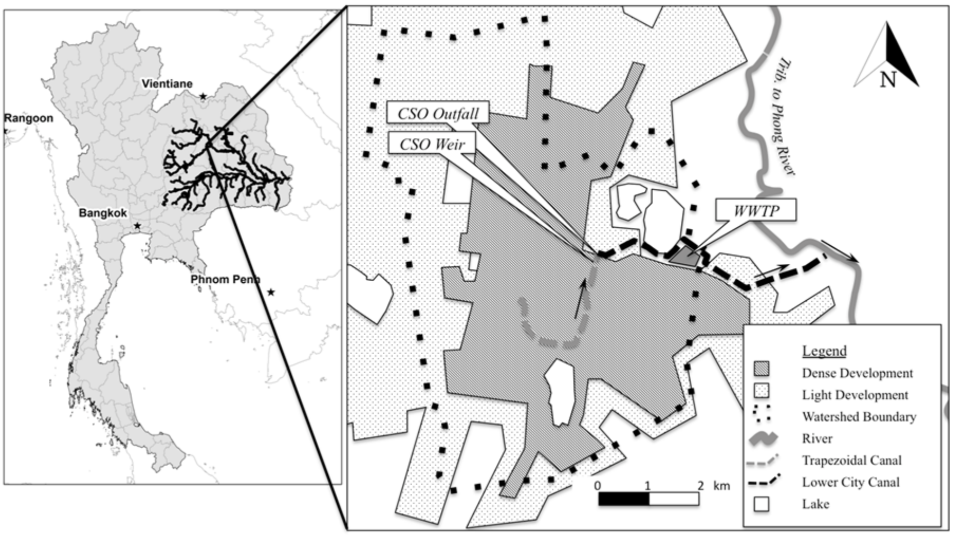


Figure 1. Study area catchment.

Chi-Mun river basin, as shown in Figure 1. The city has a population of approximately 110,000 within municipality limits and has experienced strong urbanization and growth as the regional economic, education, and governmental center of the northeast. The municipality (*thesaban*) is responsible for collecting and treating wastewater within the municipality limits.

The catchment includes about 80% of municipality limits, totaling an area of 35 square kilometers. The study catchment is comprised mostly of highly-impervious, densely-populated areas of mixed residential and commercial use with several large institutions, including a major regional university, two large hospitals, a prison, several large shopping centers, and many smaller schools and vocational colleges, as well as one large lake. The mean annual rainfall reported by the Thai Meteorological Department's weather station at Khon Kaen Airport (TMD 381201) from 1981-2010 was 1,231 mm, with 93% of that amount occurring in the seven rainy season months (April to October).

The sewer network is a combined sewer system that accepts stormwater and wastewater. The city generates between 0.4 and 0.5 cubic meters per second (m^3/s), or about 9 million gallons per day, of wastewater (350 L per capita). The wastewater primarily consists of domestic wastewater, and most buildings are required to have septic tanks; however, many unregulated discharges to the sewer system exist, due to older development or lax regulation. Historically, wastewater and urban runoff discharged to a trapezoidal canal (*rawp muang*) with base width three meters, side slope 1.5:1, and longitudinal slope 0.008 running through the city that directed flow to the Lower City Canal (*klawng lang muang*) and then to a tributary of the Phong River (a tributary of the Chi River, see Figure 1). In the early to mid-2000s the municipality covered the trapezoidal canal with a road, improved the combined sewer conveyance system's capacity by adding collectors, and built an aerated lagoon wastewater treatment plant (WWTP). The canal still serves as the main collector of the system. Immediately upstream of the WWTP's pump house, a CSO weir was built to allow wet-weather flow in excess of the WWTP's capacity to flow to a CSO outfall and discharge to the Lower City Canal. The pump house also has a gate that can be used to prevent stromwater from entering the pump house during significant flow. The height of the 6.75-meter (m) wide, suppressed rectangular weir is normally changed or removed by the municipality seasonally with perceived benefits to flood management. However, the weir was maintained at a constant height of 0.75 m for most of the study at the request of the researchers.

2.2 Water quality sampling and analysis

Water quality samples were collected during 13 sampling events from two locations, as shown in Table 1. Dry-weather samples (untreated wastewater) were collected from CSO weir's upstream pool during monthly transducer data downloads. Wet-weather samples (CSO discharge) were collected during rain events from the CSO outfall, which is approximately 200 meters downstream of the CSO weir. Wet-weather samples were collected at approximately 15-20 minute intervals until peak flow was reached and then at 20-45 minute intervals thereafter. The water at the CSO outfall is water overflowing the CSO weir and discharging to the Lower City Canal. Samples were collected by lowering a weighted bucket on a rope into the water and pouring the water into sample bottles. A total of 38 water quality samples were collected: six dry-weather samples and 32 wet-weather samples from seven rain events. One dry-weather sample (Sampling Event 4), however, was collected after a significant

Table 1. Summary of sampling events conducted during period March to August 2015.

Sampling Event	Rain Event	Date	Location	Type	Number of Samples
1	n/a	March 24, 2015	CSO Weir	Dry	1
2	1	March 30, 2015	CSO Outfall	Wet	5
3	n/a	April 22, 2015	CSO Weir	Dry	1
4	n/a	May 27, 2015	CSO Weir	Dry*	1
5	n/a	July 1, 2015	CSO Weir	Dry	1
6	2	July 8, 2015	CSO Outfall	Wet	3
7	3	July 13, 2015	CSO Outfall	Wet	5
8	n/a	July 29, 2015	CSO Weir	Dry	1
9	4	August 3, 2015	CSO Outfall	Wet	5
10	5	August 5, 2015	CSO Outfall	Wet	5
11	6	August 16, 2015	CSO Outfall	Wet	5
12	7	August 17, 2015	CSO Outfall	Wet**	4
13	n/a	August 27, 2015	CSO Weir	Dry*	1

Notes:* = Monthly wastewater sample collected after significant rainfall event. Results representative of delayed inflow and not wastewater. ** = First sample collected prior wet weather inflow, representative of wastewater. CSO = Combined sewer overflow.

rain event and was later classified as delayed wet-weather inflow.

Sampling Events 1 to 8 and 13 were collected into a laboratory-prepared 2-liter plastic bottle (all analyses except fecal coliform) or 250-millileter (mL) glass bottle (for fecal coliform), packaged into an iced cooler, and transported directly to the laboratory for sample preparation (e.g., preservation with acid, if necessary). Sampling Events 9 through 12 occurred after laboratory hours. Therefore, wet-weather samples from these rain events were collected in one of the following laboratory-prepared bottles, depending on the intended analysis: 1-liter plastic bottle with no preservative, 250-mL plastic bottle with 0.5 mL of nitric acid, 250-mL plastic bottle with 0.5 mL of sulphuric acid, or 250-mL glass bottle. The samples were kept on ice in a cooler below 4 degrees Celsius overnight and delivered to the laboratory for analysis the next morning. The holding time for all samples did not exceed 24 hours. Samples were analyzed at the Khon Kaen University Environmental Engineering Laboratory for 5-day biological oxygen demand (BOD), total suspended solids (TSS), total Kjeldahl nitrogen (TKN), total zinc, and fecal coliform (FC) based on Standard Methods (APHA, 2012). These parameters were chosen because they are some of the most commonly measured runoff pollutants in the NSQD.

2.3 Characteristics of rainfall events monitored

Seven rainfall events were sampled during the period March to August 2015 (Table 2). Rain events were defined as separated precipitation events that caused an observable response in the combined sewer system and had an inter-event time greater than two hours (Li & Adams, 2000). The rain events represented a mix of durations, inflow volumes, and antecedent dry periods (ADPs). Rain events were also characterized by rain type using weather radar images (Chumchean, Aungsuratana, Khommuang, & Hanchoowong, 2009). Rain Event 2 was a long-duration nimbostratus rain event, which is characterized by light to moderate rain intensity over a wide spatial range. Rain Events 1 and 6 were cumulus rain events, which is characterized by high rain intensity and localized spatial coverage. The other four rain events were cumulonimbus rain events, which are characterized by clusters of several localized high-intensity cells surrounded by lower intensity rainfall.

2.4 Flow classification

2.4.1 Water level measurement

Two pressure transducers with built-in data loggers were installed within and above the upstream pool of the CSO weir. One pressure transducer (OnSet HOBO U-20L-01), located below street level but above the water level, recorded barometric air pressure. The second pressure transducer (OnSet HOBO U-20-001-04) located within a stilling well below the pool's water surface recorded absolute pressure

Table 2. Characteristics of rainfall events sampled during period March to August 2015.

Rain Event	Start Date	Start Time	Type	Duration *min*	Rainfall Depth *mm*	Average Rainfall Intensity *mm/hr*	ADP *days*	Direct CSO Volume *m^3*	Delayed CSO Volume *m^3*	Total Wet Weather Inflow *m^3*	t_p *min*	t_r *min*	Q_p *m^3/s*
1	March 30, 2015	8:15 AM	Cumulus	150	16.0	6.4	8.8	25,400	5,200	25,500	150	100	4.90
2	July 7, 2015	9:15 PM	Nimbostratus	660	61.0	5.5	23.0	94,300	54,700	111,000	635	600	4.02
3	July 13, 2015	3:00 PM	Cumulonimbus	60	0.1	0.1	1.6	1,580	1,250	2,830	90	40	0.38
4	August 3, 2015	4:45 PM	Cumulonimbus	30	0.9	1.7	0.5	4,350	2,320	6,630	45	45	0.81
5	August 5, 2015	4:45 PM	Cumulonimbus	60	4.1	4.1	2.0	17,580	26,420	44,000	80	50	4.08
6	August 16, 2015	2:45 PM	Cumulus	15	1.6	6.3	3.8	10,100	8,700	18,800	60	45	2.46
7	August 17, 2015	3:00 PM	Cumulonimbus	45	2.3	3.1	1.0	6,090	6,010	12,100	65	40	1.12

Notes: m^3 = cubic meters; mm = millimeters; min = minutes; Duration = determined from TMD Khon Kaen radar station; Rainfall depth = area-weighted average of two rainfall gauges; Royal Irrigation Department Daily Rain Gauge Station 14401 (Khon Kaen City) Thai Meteorological Department 3-hour Rain Gauge Station 381201 (Khon Kaen Airport); ADP = antecedent dry period, as determined by flow measurement; tp = time to peak CSO from start of rain; tr = time to peak CSO from start of wet weather inflow; Qp = peak CSO flow rate.

(the sum of water pressure and air pressure).

An algorithm in the manufacturer's software (HOBOware PRC software v.3.7.4) calculated water level depth in the weir pool from the two transducers' data. Both pressure transducers were set to log data at 5-minute intervals. Data was downloaded from the transducers once per month. Water level data were collected continuously from December 2014 to August 2015 with some gaps when the stilling well was damaged by debris or the weir was removed for maintenance.

2.4.2 CSO flow rate calculation

The Kindsvater-Carter weir equation (Kindsvater & Carter, 1959) was used to calculate the CSO flow rate from the weir pool height (h), as shown in Equation 1.

$$Q_{cso} = C_d \tfrac{2}{3}\sqrt{2g}\,(b + K_b)(H + K_h)^{3/2} \tag{1}$$

where b is the weir width (6.75 m) and H is the head above the weir crest. K_b and K_h are the effective width and effective height coefficients, respectively, which account for viscosity and surface tension effects. For a suppressed weir, K_b is -0.001 meters (m) and K_h is +0.001 m. K_b was neglected because it is negligible for this size weir. The discharge coefficient, C_d, was calculated using the Rehbock equation (Schoder & Turner, 1929), as shown in Equation 2.

$$C_d = 0.602 + 0.983(H/Y) \tag{2}$$

where Y is the weir height (0.75 m). The Kindsvater-Carter weir equation is recommended by the International Organization for Standardization and U.S. Bureau of Reclamation, because it accounts for velocity of approach effects and the accompanying variation of discharge coefficient caused by changes of effective width and head (International Organization for Standardization [ISO], 2008; United States Bureau of Reclamation [USBR], 2001). Flow rate estimates were validated using an electromagnetic open channel velocity meter (Valeport Model 801).

2.4.3 Inflow flow rate calculation

Total wet-weather inflow to the trapezoidal canal was calculated using the principle of flow continuity using the CSO flow rate described above. Flow continuity (Eq. 3) was used to calculate the wet-weather inflow flow rate (Q_{in}) as a function of the CSO flow rate (Q_{cso}), net wastewater flow rate (Q^*_{ww}), and change in volume of water within the trapezoidal channel (ΔV), calculated from the weir pool height and channel dimensions. The change in volume was calculated at 5-minute intervals (Δt).

$$Q_{in} = \left(\Delta V/\Delta t\right) + Q_{cso} - Q^*_{ww} \tag{3}$$

The net wastewater flow rate was normally zero (i.e., flow out of the combined sewer system to the WWTP was effectively equal to wastewater generated and flowing into the system); however, during some rain events, the WWTP pump house door was closed by the municipality, preventing flow from exiting the system to the WWTP. Thus, the net flow rate was equal to the typical wastewater generation rate of the city, 0.4 m^3/s.

2.4.4 Flow classification and hydrograph separation

Flow conditions in a combined sewer system can generally be classified as either dry-weather flow or wet-weather flow. The wet-weather flow can further be classified into two subgroups: direct inflow and delayed inflow (Metcalf & Eddy *et al.*, 2003). Thus, a total of three possible classifications were considered for the flow regime: dry-weather wastewater flow, direct wet-weather inflow, and delayed wet-weather inflow.

A visual inspection of the system hydrograph was used to identify periods of wet-weather flow, in which the flow rate diverges from typical flow with diurnal variations. Direct inflow was classified as beginning at the initial hydrograph increase and ending 1.75 hours (the maximum observed system hydrologic response time) after the conclusion of the storm. Delayed inflow was classified as the remainder of the inflow until the hydrograph converged to the dry-weather pattern.

In some cases, hydrographs from two storms overlapped, and it was necessary to separate the two hydrographs. The trailing end of a hydrograph follows a exponential decay (Ponce, 1989). Therefore, regression was used to fit an exponential relationship to the decay and estimate the flow rate from the first storm and subtract it from the hydrograph to calculate flow attributable to the second storm, as shown in Figure 2.

2.5 Statistical methods

2.5.1 General statistics and data analysis

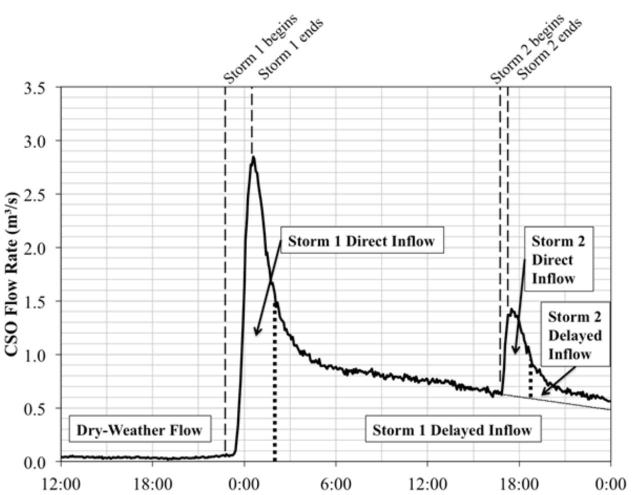


Figure 2. Example of hydrograph separation and flow regime classification.

Descriptive statistics (minimum, maximum, arithmetic mean and standard deviation) were calculated for each water quality parameter. In addition, descriptive statistics (arithmetic mean and interquartile range, IQR) for each parameter were calculated within the sub-groups representing each of the three flow classifications. Measured concentrations collected during overlapping hydrographs were corrected using mass balance (Equation 4) to account for dilution of the direct inflow by the previous storm's delayed inflow.

$$C_{corr} = \frac{C_{meas}Q_{cso} - C_{prev}Q_{prev}}{Q_{cso} - Q_{prev}} \tag{4}$$

where C_{corr} and C_{meas} are the corrected and measured concentration, respectively, and C_{prev} and Q_{prev} are the measured concentration and flow rate before the beginning of inflow, respectively. If a parameter was not detected in a sample, a value of half of the detection limit was used in statistical analyses. Outliers were identified using Tukey's method (Tukey, 1977).

2.5.2 Event mean concentrations

The calculation of event mean concentration (EMC) represents a flow-weighted average concentration of the pollutant over the duration of the storm event. EMC is calculated from Equation 5:

$$EMC = \frac{\sum_{i=1}^{N} \overline{c_l}\,\overline{Q_l}\Delta t_i}{\sum_{i=1}^{N} \overline{Q_l}\Delta t_i} \tag{5}$$

in which N and Δt_i represent the number of samples and time interval between consecutive samples, respectively. $\overline{c_l}$ and $\overline{Q_l}$ the central-weighted average of pollutant concentration and central-weighted average of flow rates over the sample time intervals, respectively. EMC was calculated using only direct inflow.

2.5.3 Correlation analysis

Correlation between parameters was used to infer whether pollutant concentrations may be affected by similar physical processes. The degree of correlation between parameters was assessed using Pearson's correlation coefficient, computed in a statistical package. Pearson's r was calculated for each parameter pair using the subset of results from direct inflow.

3. Results

3.1 Characteristics of water quality

Summary statistics of the collected samples are presented in Table 3. Eight of the 38 samples (21%) had concentrations of zinc below the method detection limit (0.03 mg/L). A value of half of the detection limit (0.015 mg/L) was used in statistical analyses. No other results were below the detection limit. Two results of fecal coliform were identified as outliers and were not included in summary statistics or correlation analysis. No other outliers were identified.

Explicit water quality standards applicable to CSO discharges do not exist. Therefore, three similar surface water quality standards from the Thai Pollution Control Department (PCD) are provided in Table 3 for reference: the treated effluent standard for a large housing state, industrial effluent, and the water quality standard for the receiving body of water, the Phong and Chi Rivers, which are classified as Class 3 surface water bodies. The arithmetic means computed from all samples exceed the large housing estate standard and industrial effluent standard for BOD (51.0 mg/L) and TSS (175 mg/L).

Event mean concentrations (EMCs) of the seven sampled rain events show variation of several magnitudes in each parameter except TKN (Table 4). Rain events 3 and 4 were small rainfall events (less than 1 mm) with short

Table 3. Summary statistics of surface water quality in Khon Kaen catchment.

Parameters	BOD *mg/L*	TSS *mg/L*	TKN *mg/L*	Zinc[1] *mg/L*	Fecal Coliform[2] *MPN/100mL (Log-10)*
Minimum	15.6	20	4.0	<0.03	5.3
Maximum	132.0	788	49.3	0.74	7.8
Arithmetic Mean - All Samples (n = 38)	51.0	175	14.0	0.18	6.7
Arithmetic Mean - Direct Inflow (n = 26)	59.4	239	11.8	0.24	6.9
Standard Deviation - All Samples (n =38)	29.6	189	8.3	0.19	0.7
Standard Deviation - Direct Inflow (n = 26)	30.9	196	4.0	0.19	0.5
PCD Housing Estate Effluent Standard (>500 units)	20	30	35	n/a	n/a
PCD Industrial Effluent Standard	20-60	50-150	100-200	5	n/a
PCD Class 3 Surface Water Standard	2	n/a	n/a	1	3.6

Notes: 1 = Eight results were below the detection limit (0.03 mg/L). Half the detection limit was used in computations.
2 = Two results from fecal coliform were excluded from all analyses as outliers. mg/L = milligrams per liter; MPN/100 mL = most probable number per 100 milliliters; PCD = Thai Pollution Control Department.

Table 4. Event mean concentrations (EMCs) of combined sewer flow during direct inflow of monitored rainfall events in Khon Kaen catchment.

Event	Date	Characterized[1] %	BOD[2] *mg/L*	TSS[3] *mg/L*	TKN[4] *mg/L*	Zinc[5] *mg/L*	FC[6] *MPN/100mL*
1	March 30, 2015	87%	80.5	414	16.6	0.44	1.3E+08
2	July 8, 2015	20%	n/a	n/a	n/a	n/a	n/a
3	July 13, 2015	68%	45.0	81	12.7	0.04	8.6E+06
4	August 3, 2015	84%	47.2	179	11.5	0.17	1.5E+07
5	August 5, 2015	100%	92.8	512	12.9	0.46	2.2E+07
6	August 16, 2015	100%	68.3	276	13.4	0.29	6.3E+06
7	August 17, 2015	67%	n/s	192	10.4	0.25	n/s
Dry	March to August 2015	n/a	48.9	31	29.1	0.02	1.6E+07
Delayed	March to August 2015	n/a	23.7	36	11.2	0.04	2.8E+06
PCD Housing Estate Effluent Standard (>500 units)			20	30	35	n/a	n/a
PCD Industrial Effluent Standard			20-60	50-150	100-200	5	n/a
PCD Class 3 Surface Water Standard			2	n/a	n/a	1	4000

Notes: 1 = Percentage of CSO volume characterized, as determined by volume between first and last sample. 2 = 5-day biological oxygen demand. Incubate at 20 deg C, 5 days and Azide Modification. 3 = total suspended solids. Thai Industrial Standard Institute Standard Method 2540 D. 4 = total Kjeldahl nitrogen. Kjeldahl Method. 5 = total zinc. Flame atomic absorption spectrometer method. 6 = fecal coliform. Multiple tube fermentation technique. n/a = Not applicable. n/s = Not sampled. mg/L = milligrams per liter. MPN/100 mL = most probable number per 100 milliliters. PCD = Thai Pollution Control Department.

durations (60 and 30 minutes, respectively). The EMCs for these events were similar to dry-weather flow and were lower than the EMCs during Rain Events 1 and 5, which had more rainfall (16.0 and 4.1 mm) and longer durations (150 and 60 minutes). Rain events 6 and 7 also had short durations (15 and 45 minutes) but had moderate rainfall depth (1.6 and 2.3 mm). Similarly, the EMCs were in the middle of the observed range for all parameters except TKN. Generally, higher EMCs were observed during higher depth rain events. EMCs for Rain Event 2 could not be calculated because not enough samples were collected to adequately characterize the long-duration rain event.

3.2 Comparison of direct and delayed inflow against untreated wastewater

Samples were categorized based on the flow classification at the time of the sample. A comparison of the summary statistics (arithmetic mean and interquartile range) from each flow classification is displayed in Figure 3.

The mean concentrations during direct inflow of total zinc ($\overline{x}$ = 0.24 mg/L), TSS ($\overline{x}$ = 240 mg/L), and—to a lesser degree—BOD ($\overline{x}$ = 59.7 mg/L) are dramatically higher when compared to wastewater ($\overline{x}$ < 0.03 mg/L, 31 mg/L, and 48.9 mg/L, respectively); fecal coliform was effectively unchanged (1.4×10^7 vs. 1.6×10^7 MPN/ 100mL); and TKN was lower (29.1 mg/L to 11.8 mg/L). When comparing direct inflow to delayed inflow, the concentration for all parameters except TKN is dramatically lower during delayed inflow; concentrations of TKN are unchanged.

3.3 Pollutograph analysis of CSO events

Pollutographs (combination of flow and concentrations graphs) for BOD, TSS, TKN, and total zinc are displayed in Figure 4 for the three largest rainfall events in which all five parameters were measured (Rain Events 1, 5, and 6). Generally, the trend in pollutant concentration follows the trend in flow hydrograph. The timing of the peak concentration of these parameters closely coincides with the peak flow rate of rain events. The peak concentration of TKN and BOD precede the peak in flow in Rain Event 5 (Figure 4(b)). However, in all other cases, the peak concentration of pollutants is coincident or after the peak flow rate.

3.4 Correlation between water quality parameters

Pearson's correlation (r) between water quality parameters calculated from results of direct inflow sampling are reported in Table 5. All parameters exhibited positive correlations to other parameters. TSS and total zinc demonstrated a very strong correlation (r = 0.909). BOD also correlated very strongly with TSS (r = 0.885). These three

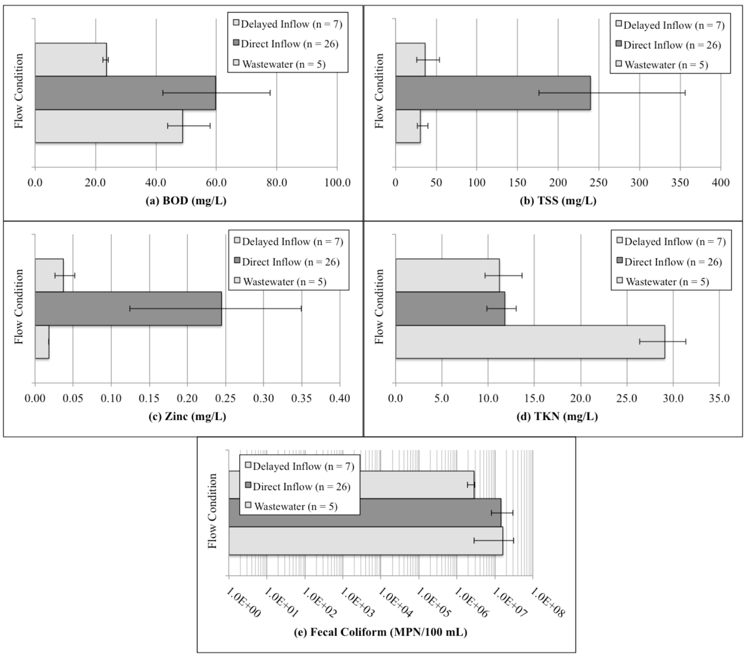
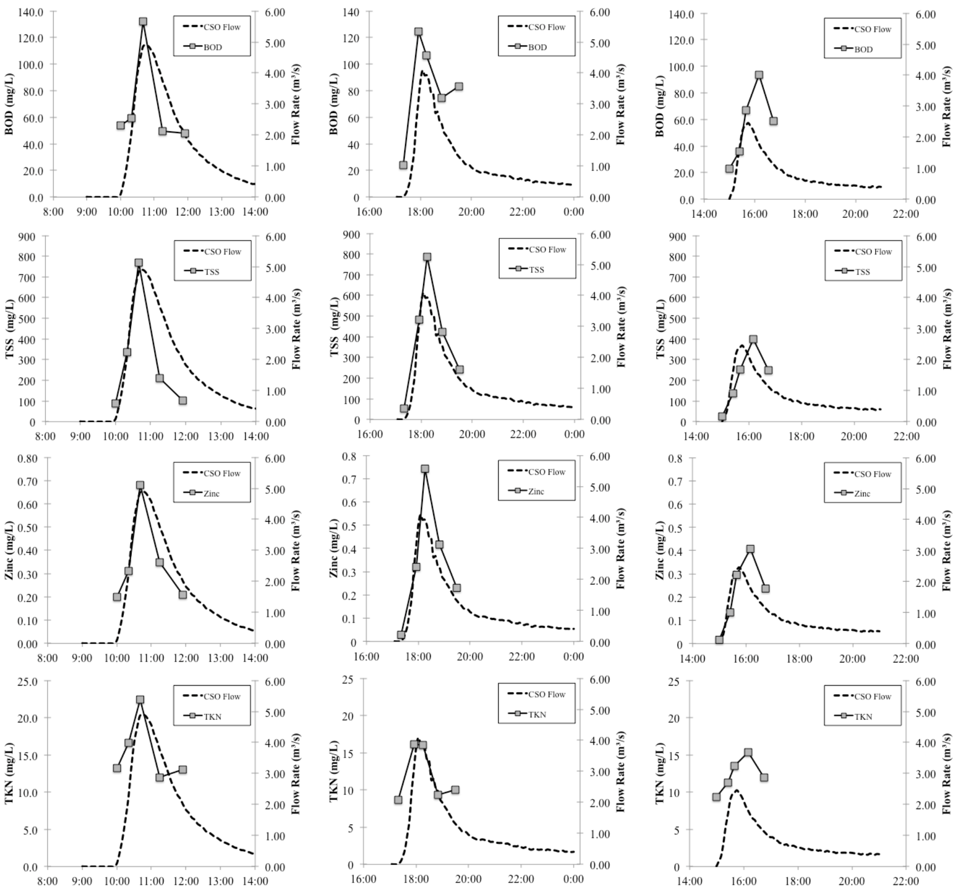


Figure 3. Comparison of pollutant concentrations (mean and interquartile range) between flow regime classifications.



(a) Rain Event 1 (3/30/15)
depth = 16.0 mm
duration = 150 min

(b) Rain Event 5 (8/5/15)
depth = 4.1 mm
duration = 60 min

(c) Rain Event 6 (8/16/15)
depth = 1.6 mm
duration = 15 min

Figure 4. Pollutographs from selected rainfall events.

Table 5. Correlation coefficients between water quality parameters.

	BOD	TSS	Zinc	TKN	FC
BOD	—	**0.885** **	**0.762** **	**0.769** **	0.418
TSS	**0.885** **	—	**0.909** ***	0.669 *	0.583 *
Zinc	**0.762** **	**0.909** ***	—	0.535 *	0.551 *
TKN	**0.769** **	0.669 *	0.535 *	—	0.581 *
FC	0.418	0.583 *	0.551 *	0.581 *	—

Notes: * = Correlation coefficient greater than 0.5. ** = Correlation coefficient greater than 0.7. *** = Correlation coefficient greater than 0.9.

parameters (BOD, TSS, and zinc) have a high level of correlation ($r > 0.70$) with each other and represent one group of pollutants. TKN correlated strongly ($r = 0.769$) with BOD and moderately with TSS ($r = 0.669$) but not with zinc. Fecal coliform did not correlate strongly with any other parameter. Overall, TSS correlated the most with all measured parameters. The correlation coefficients between parameters during delayed inflow were lower.

4. Discussion

While both direct and delayed inflows generated significant volumes of CSO discharge from this catchment, the resulting mass discharge were dissimilar. The results demonstrate that pollutant concentrations during direct inflow and delayed inflow phases of wet-weather flow within combined sewer systems are notably different and likely represent different phenomenon. The data also provides an opportunity to infer the sources of the contaminants.

Pollutants within CSO discharge can be derived from three primary sources: pollution directly contained within runoff waters, pollution within wastewater that mixes with stormwater, and pollution derived from the erosion of in-sewer pollutant stocks (Chebbo *et al.*, 2001). The in-sewer pollutant stocks can further be classified into three primary types: granular sediment and deposits at the bottom of the sewer pipe (Type A + B), organic sediments on top of the granular sediment located at the sediment-water interface (Type C, or organic layer), and an organic slime or biofilm located on the walls at the mean water level (Type D) (Crabtree, 1989). Pollutant types and concentrations in CSO discharge will vary depending on the source of the pollutants.

The concentrations of TSS and zinc during direct inflow are several times higher than that of wastewater or delayed inflow. The concentrations also closely follow trends in flow rate. Previous research has shown that suspended solids (Crabtree, Moy, Whitehead, & Roe, 2006) and zinc (Förster, 1996) can originate at significant concentrations from streets (for both) and roofs (for zinc). However, in-sewer physical and chemical processes, such as settling and flocculation, deposit these pollutants in Type A deposits that are flushed during high-velocity wet-weather flow (Chebbo *et al.*, 2001). Therefore, the results suggest TSS and zinc, which correlate strongly with each other, likely originate from the same source—primarily from Type A granular deposits in the sewer. Type A deposits appear less significant during delayed inflow.

Oxygen-consuming matter (i.e., BOD) has also been shown to originate from in-sewer stocks (Chebbo *et al.*, 2001). BOD was correlated with zinc and TSS, suggesting it may also be related to re-suspended sediment. However, during storm events BOD did not continue to decrease from its peak, like TSS and zinc did. Instead, it maintained a plateau at concentrations higher than wastewater before decreasing. Therefore, BOD may also originate from more cohesive Type C deposits that constitute the majority of the sewer's organic matter (Ahyerre, Chebbo, & Saad, 2001).

TKN concentrations in direct and delayed inflow were, on average, less than half the concentration found in wastewater. Therefore, TKN and other nutrients are not likely found at high concentrations in runoff, similar to values found in the NSQD (Pitt & Maestre, 2004). The catchment contains very few parks or other residential areas, and the use of fertilizers is not common in urban areas of the city, which likely explains the relatively low concentrations of TKN in runoff. Notably, the EMC of TKN from Rain Event 1 was higher than the EMC of TKN from Rain Event 5, which was similar in rain depth and peak flow rate. However, other pollutants (BOD, TSS, and zinc) had higher EMCs in Rain Event 5. Rain Event 1 had a much longer ADP and occurred early in the rain season when atmospheric deposition is more significant, suggesting washoff of atmospheric deposition may be more significant of a source of nutrients than resuspension of in-sewer deposits. Generally, the EMC of TKN seems to be related mostly to ADP, rather than rainfall depth, duration, or intensity.

These inferences have important implications for considering options for managing CSO pollution. The most common approach in cities to reduce untreated CSO discharge is to capture the initial component of flow in a detention facility for treatment; however, the size and hydraulic control apparatus would differ depending if the target is suspended solids and adsorbed metals.

5. Conclusions

Data collected during wet-weather flow in a combined sewer catchment of Thailand demonstrated that pollutant concentrations for particulate-based pollutants were much higher during the direct inflow phase of rain events compared to the delayed inflow phase. Dissolved-phased nutrients, however, were not different. Thus, for some parameters, regulators and researchers cannot consider all wet-weather flow in combined sewer systems equally, but they should distinguish between direct and delayed inflow. In fact, the water quality is overall better in delayed inflow CSO discharge compared to untreated wastewater. However, the research confirms that CSO discharges during the direct inflow portion of rain events introduces significant mass of particulate matter and related pollutants to the environment and that the CSO effluent does not meet related Thai PCD standards for BOD or TSS. The re-suspension of in-sewer sediment and organic layers is likely a significant source of pollutants in CSO events. Further investigation is necessary to better understand pollutant sources. Additionally, the development of a hydrologic and water quality model from this data will benefit stakeholders.

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