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Calibration of parsimonious water quality model to estimate seasonal TSS loading in a combined sewer system: case study in Khon Kaen, Thailand

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Abstract

A parsimonious water quality model was calibrated and validated to 36 samples analyzed for total suspended solids (TSS) collected from the Khon Kaen's combined sewer system during 12 sampling events from June 1 to October 28, 2015. TSS concentrations were simulated using observed flow rates in the sewer as the input, computed continuously at 5-minute time steps. The calibrated model was then used to estimate the seasonal mass loading of TSS through the system and percentage of which that was sent to the wastewater treatment plant (WWTP) for treatment. Calibration achieved a Nash-Sutcliffe Efficiency value of 0.74, while validation achieved 0.54. The modelling results estimated that 537,000 kilograms of particulate matter were transported via 11.8 million cubic meters (m^3) of stormwater and wastewater that discharged through the sewer system (average concentration of 45.7 mg/L) from June to October 2015. Calculations also estimated that 44% of the particulate matter was collected by the WWTP.

Keywords: combined sewer system; modelling; pollutant concentrations; Thailand; water quality

1. Introduction

Water quality models are important tools to municipal engineers and urban planners for estimating wastewater conveyance and treatment capacity [1], [2] & [3]. Several modelling approaches exist [4], from relatively simple empirical and statistical approaches [5] to complex, physically based models, such as EPA's SWMM [6]. These spatially distributed models are often difficult to accurately use, however, due to limited water quality measurements and uncertainties throughout the physical sewer system [7]. Overparameritization (i.e., a greater number of model parameters than warranted by available data) is problematic [8]. Thus, parsimonious modelling (i.e., limiting the number of processes and parameters) offers a preferable approach to water quality modelling that introduces less uncertainty while still adequately reproducing observed results [9] & [10].

Commonly, urban water quality models use buildup-washoff functions to simulate pollutant concentrations [11] & [12]. One such parsimonious buildup-washoff model was developed and demonstrated in a temperate, small-size urban catchment in Belgium [13]. It has not yet been demonstrated in a tropical climate or catchment of a developing nation, where rainfall patterns generate different runoff signatures and land use patterns differ from those of Europe.

The objectives of this case study were to 1) calibrate the existing parsimonious water quality model to a midsize urban catchment in a tropical climate with a winter dry season and 2) use the model to estimate seasonal loading of particulate matter through the combined sewer system. The purpose of this study was to demonstrate the viability of this water quality model to this catchment, so that it can be paired with a rainfall-runoff model under development to predict pollutant concentrations from rainfall data.

2. Materials and Methods

The model was calibrated to 36 water quality samples collected from the combined sewer system from June to October 2015. Results from the model were generated using input of combined sewer flow rates that were continuously monitored over the same time period. The following section describes the methods in detail.

2.1. Description of Study Catchment

Khon Kaen, located in northeast Thailand, has a population of approximately 110,000 within municipality limits. The city consists mostly of highly impervious, densely populated areas of mixed residential and commercial use. The mean annual rainfall reported by the Thai Meteorologial Department's weather station at nearby Khon Kaen Airport (TMD 381201) from 1981-2010 was 1231 mm, with 72% of the total average rainfall occurring between June and October.

The city's 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 per day). Historically, wastewater and urban runoff were discharged to a trapezoidal canal (*rawp muang*) with base width 3 meters, side slope 1.5:1, and longitudinal slope 0.008 running through the city that flowed directly to the Lower City Canal (*klawng lang muang*), which discharges to a tributary of the Phong 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 trapezoidal canal still serves as the main collector of the sewer system. Immediately upstream of the WWTP's pump house, which typically operates at 0.55 m^3/s, a combined sewer overflow (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 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 the duration of the study at the request of the researchers.

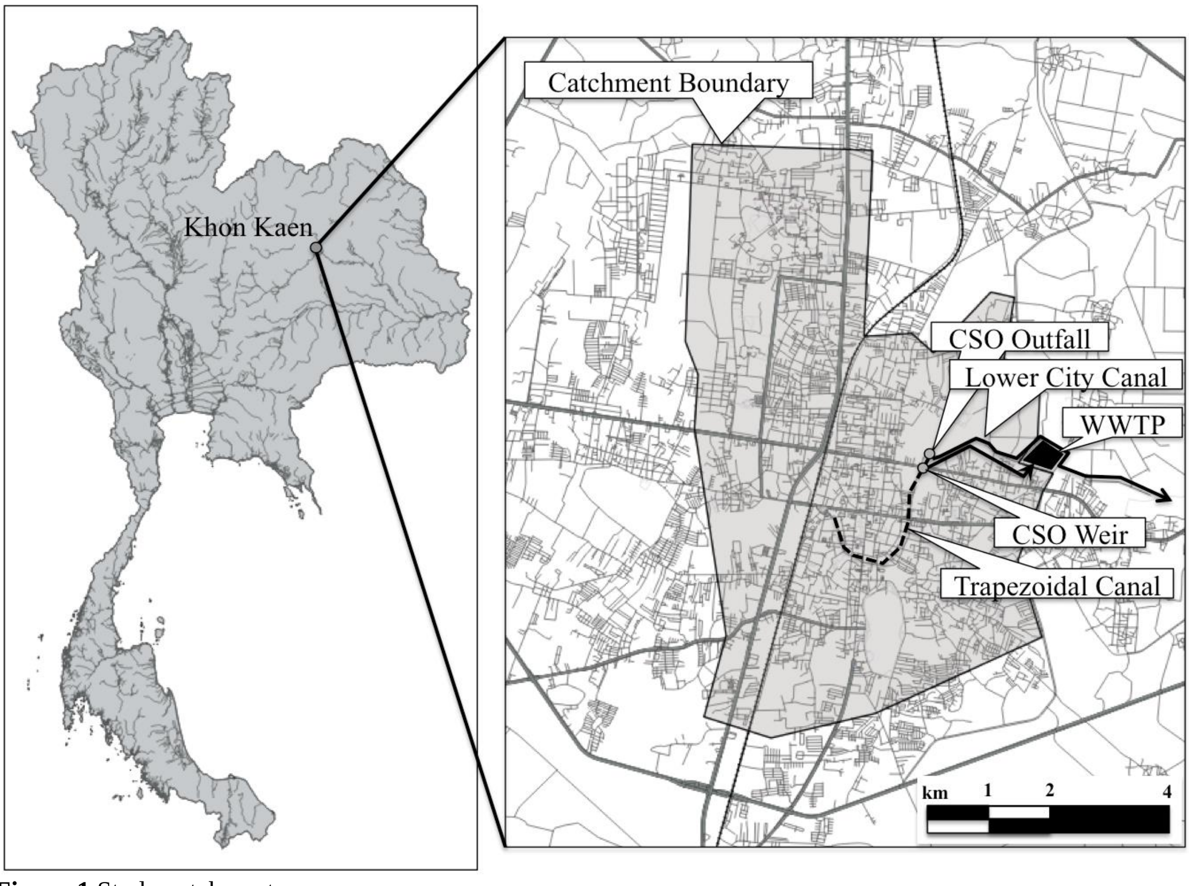

Figure 1 Study catchment

Table 1 Summary of sampling events

Sampling Event	Rain Event	Date	Location	Number of Samples	Cal/Val
1	n/a	July 1, 2015	CSO Weir	1	Cal
2	1	July 8, 2015	CSO Outfall	3	Val
3	2	July 13, 2015	CSO Outfall	5	Cal
4	n/a	July 29, 2015	CSO Weir	1	Val
5	3	August 3, 2015	CSO Outfall	5	Val
6	4	August 5, 2015	CSO Outfall	5	Cal
7	5	August 16, 2015	CSO Outfall	5	Cal
8	6	August 17, 2015	CSO Outfall	4	Val
9	n/a	August 27, 2015	CSO Weir	1	Cal
10	7	September 27, 2015	CSO Outfall	4	Cal
11	n/a	September 29, 2015	CSO Weir	1	Val
12	n/a	October 28, 2015	CSO Weir	1	Cal

Notes:

CSO = Combined sewer overflow

Cal/Val = Sampling event data used in model calibration (Cal) or validation (Val)

2.2. Water Quality Sampling and Analysis

Water quality samples were collected during 12 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 36 water quality samples were collected: 5 dry-weather samples and 31 wet-weather samples from 7 rain events.

Sampling Events 1-4, 8-9, and 11-12 were collected into a laboratory-prepared 2-liter plastic bottle, packaged into an iced cooler, and transported directly to the laboratory for sample preparation (i.e., characterized, homogenized, and poured into a 1-L unpreserved plastic bottle). Sampling Events 5-7 and 10 ended after laboratory hours. Therefore, samples from these rain events were collected in 1-liter plastic bottle with no preservative. 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 total suspended solids (TSS) based on Standard Methods [14].

2.3. Flow Rate Monitoring

The total discharge of the combined sewer system consists of two main components: 1) a relatively constant flow rate to the WWTP (assumed to be constant at 0.55 m^3/s for this study) maintained by pumps and 2) discharge overflowing the CSO weir to the receiving water body.

The CSO flow rate was computed by monitoring the water level upstream of the CSO weir. 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 (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 May 25, 2015 to October 28, 2015.

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

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

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, that account for viscosity and surface tension effects. For a supressed 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 [15], as shown in Equation 2.

$$C_d = 0.602 + 0.083(H/Y) \quad (2)$$

Where Y is the weir height (0.75 m). Flow rate estimates were validated using an electromagnetic open channel velocity meter (Valeport Model 801).

2.4. Parsimonious Buildup and Washoff Model

An existing parsimonious lumped buildup and washoff model that was developed for combined sewer overflow pollution was used in this case study (13). The model is based on the concept of linear reservoir modelling and was demonstrated for TSS on a small urban catchment in Belgium. The model lumps together deposition, washoff, and other sewer transport processes into a single equation. It considers the combined pollutant deposit (z) at the catchment surface and in the sewer system as the main variable, described in Equation 3.

$$\frac{dz}{dt} = a(z - \bar{z}) + b(q - \bar{q}) \quad (3)$$

The parameter $\bar{z}$ represents the mean pollution deposit, and $\bar{q}$ represents the sewer flow rate (q) at which pollutant resuspension occurs. The derivative (dz/dt) is the growth (or decay) rate of pollution buildup. The coefficients a and b are negative. Thus, $q > \bar{q}$ represents pollutant resuspension and $q < \bar{q}$ represents pollutant deposition. The value of $\bar{q}$ can be assumed to be equal to the maximum dry weather flow discharge (13).

Equation (3) can be transformed to the linear reservoir model equation (Equation 4) by setting $a = -1/k$.

$$\frac{dz}{dt} = -\frac{1}{k}(z - z_{in}) \quad (4)$$

The incoming pollutant mass rate, z_{in}, is described using Equation 5:

$$z_{in} = \bar{z} + kb(q - \bar{q}) \quad (5)$$

The parameter b is also a function of z (Equation 6).

$$b = b_{max}(1 - e^{-\frac{z}{k_b}}) \quad (6)$$

The value of b_{max} can be one of two values, depending on if the system is in resuspension (b_{max1}) or deposition (b_{max2}), as shown in Equation 7.

$$b_{max} = \begin{cases} b_{max1}, q > \bar{q} \\ b_{max2}, q < \bar{q} \end{cases} \quad (7)$$

The amount of pollutant deposits (z) is then iteratively solved for each time step using the value of dz/dt, which can be found from Equations 4-7. The pollutant washoff rate, y, is simply equal to $-dz/dt$ when $dz/dt < 0$ (i.e., washoff) and equal to zero when $dz/dt > 0$ (i.e., buildup). Finally, the model-predicted concentration of TSS (C_{TSS}) was calculated by mass balancing the washoff with the dry-weather flow (dry-weather flow rate, q_{dwf} = 0.55 m^3/s and concentration of TSS in dry-weather flow, C_{dwf} = 31 mg/L, which were calculated from observations of dry weather flow), as shown in Equation 8.

$$C_{Tss} = \left[y\left(q - q_{dwf}\right) + c_{dwf} q_{dwf}\right] / q \tag{8}$$

Thus, the model gives simulation results with characteristics qualitatively similar to sewer processes (exponential increase in mass during buildup, exponential decrease in mass during washoff, and increased pollutant washoff with increased flow intensity) with relatively few parameters to calibrate to, namely k, k_b, $\bar{q}$, $\bar{z}$, b_{max1}, and b_{max2} (13). It also only requires sewer flow rate (q) as input.

2.5. Model Calibration and Validation

The model simulated TSS concentrations via a continuous simulation of the period June 1, 2015 to October 28, 2015 using 5-minute time steps. A 2-day warmup period (starting May 30, 2015) was provided to the model using the initial condition of $z = 0.7*\bar{z}$. The forcing input for the model was the observed combined sewer flow rate (q). The optimization parameter was the Nash-Sutcliffe efficiency parameter (NSE), which is calculated using Equation 9.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(C_{TSS,i}^{obs} - C_{TSS,i}^{sim})^2}{\sum_{i=1}^{n}(C_{TSS,i}^{obs} - \bar{C}_{TSS}^{obs})^2}\right] \tag{9}$$

Where $C_{TSS,i}^{obs}$ is the *i*th measured observation of TSS concentration, $C_{TSS,i}^{sim}$ is the *i*th simulated concentration of TSS, and $\bar{C}_{TSS}^{obs}$ is the mean observed TSS concentration. The optimum value of NSE is 1, with values greater than 0.5 recommended as an acceptable value for calibration and validation [16].

Approximately half of the sampling events were used for each model calibration and validation, with near equal distribution of wet-weather and dry-weather sampling events. Sampling Events 1, 3, 6, 7, 9, 10, 12 were used for calibration. Sampling Events 2, 4, 5, 8, 11 were used for validation.

2.6. Model Application: Seasonal Mass Loading

The calibrated and validated model was used to estimate: 1) the total mass loading of TSS conveyed through the sewer system; and 2) the proportion of TSS mass that was sent to the WWTP for treatment from June 1, 2015 to October 28, 2015.

3. Results

3.1. Model Calibration and Validation

The model was calibrated to seven sampling events (shown in Figure 2a). The calibrated model parameters are reported in Table 2. The optimum value of NSE achieved during calibration was 0.74. The model was then validated to the remaining five sampling events (shown in Figure 2b). The value of NSE during validation was 0.54. A plot of all model-estimated and observed TSS concentrations is shown in Figure 3. If the model perfectly predicted the TSS concentration, the points would all fall on the 1:1 line.

3.2. Estimate of Seasonal Loading of TSS in Sewer System

The seasonal loading (June to October) of TSS through the combined sewer system was estimated by summing the mass loading rate (product of concentration and flow rate) for the entire continuous simulation. The results of the continuous simulation are displayed in Figure 4. Additionally, a comparison of estimated total time, flow volume, TSS mass, and percent that is treated by the WWTP were estimated among categories of flow that exceed specified flow rates (from less than 1 m^3/s to greater than 15 m^3/s), as shown in Table 3. The categorization of flow allows stakeholders to identify flow regimes of concern for mass loading or discharge of untreated pollutants to the receiving surface water body.

The results show that from June 1 to October 28, 2015, it is estimated that about 11.8 million m^3 of stormwater and wastewater discharged from the sewer system, which transported about 537,000 kilograms (kg) of particulate matter (average concentration of 45.7 mg/L). The flow classification with the highest TSS concentration was flow greater than or equal to 3 m^3/s, which had an average concentration of 134.6 mg/L. While the flow rate was less than 1 m^3/s (i.e., essentially dry-weather flow) 81.1% of the time, it only accounted for 62.9% of the total flow volume and 36.6% of the particulate mass. On the other hand, wet-weather flow (i.e., flow greater than or equal to 1m^3/s) occurred 18.9% of the time, but accounted for 37.1% of the flow volume and 63.4% of the particulate mass.

Overall, it is estimated that about 44% of the total TSS mass discharged from the sewer system over the five-month time period was sent to the WWTP for treatment, which means about 300,000 kg of particulate matter was discharged to the receiving water body without treatment.

Table 2 Parameter values of water quality model after calibration

Model Parameter		Value	
C_{dwf}	average dry weather TSS concentration	31	mg/L
q_{dwf}	average dry weather flow rate	0.55	m³/s
k	reservoir constant (mass deposit)	32	h
k_b	reservoir constant (washoff or deposition)	1300	h
$\bar{z}$	mean pollution mass deposit	23,000	kg
$b_{max,1}$	maximum washoff/ resuspension concentration	1900	mg/L
$b_{max,2}$	maximum deposition concentration	40	mg/L
$\bar{q}$	maximum dry weather flow or critical shear stress	0.73	m³/s

Table 3 Model-estimated time, cumulative flow volume, and cumulative mass for simulation period (June 1 to October 28, 2015), classified by flow rate exceedance

Flow Condition	Time		Flow Volume		Mass TSS		Avg. TSS	% to WTTP
	min	*% Total*	*m³*	*% Total*	*kg*	*% Total*	*mg/L*	*% Mass*
Flow < 1m³/s	174,480	81.1%	7,390,564	62.9%	196,388	36.6%	26.6	78.2%
Flow ≥ 1m³/s	40,670	18.9%	4,363,016	37.1%	340,213	63.4%	78.0	24.6%
Flow ≥ 2m³/s	8,485	3.9%	1,902,935	16.2%	207,141	38.6%	108.9	13.7%
Flow ≥ 3m³/s	3,315	1.5%	1,147,091	9.8%	154,344	28.8%	134.6	10.8%
Flow ≥ 5m³/s	1,190	0.6%	675,541	5.7%	86,556	16.1%	128.1	7.3%
Flow ≥ 7m³/s	695	0.3%	501,191	4.3%	51,489	9.6%	102.7	5.9%
Flow ≥ 10m³/s	315	0.1%	310,182	2.6%	10,141	1.9%	32.7	4.2%
Flow ≥ 15m³/s	175	0.1%	207,569	1.8%	2,587	0.5%	12.5	3.0%
Total	215,150		11,753,580		536,601		45.7	44.2%

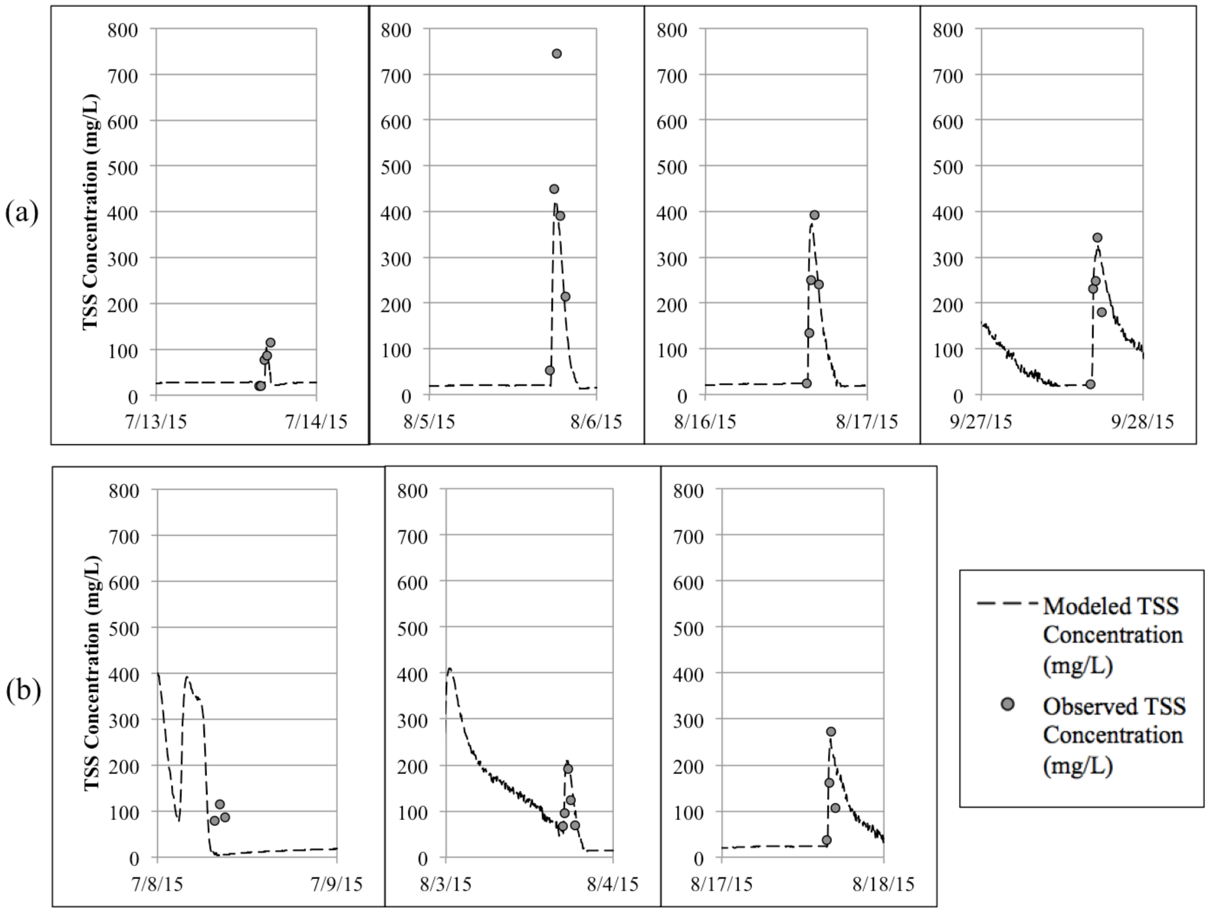

Figure 2 Pollutographs of observed and model-simulated TSS concentrations from (a) model calibration and (b) model validation

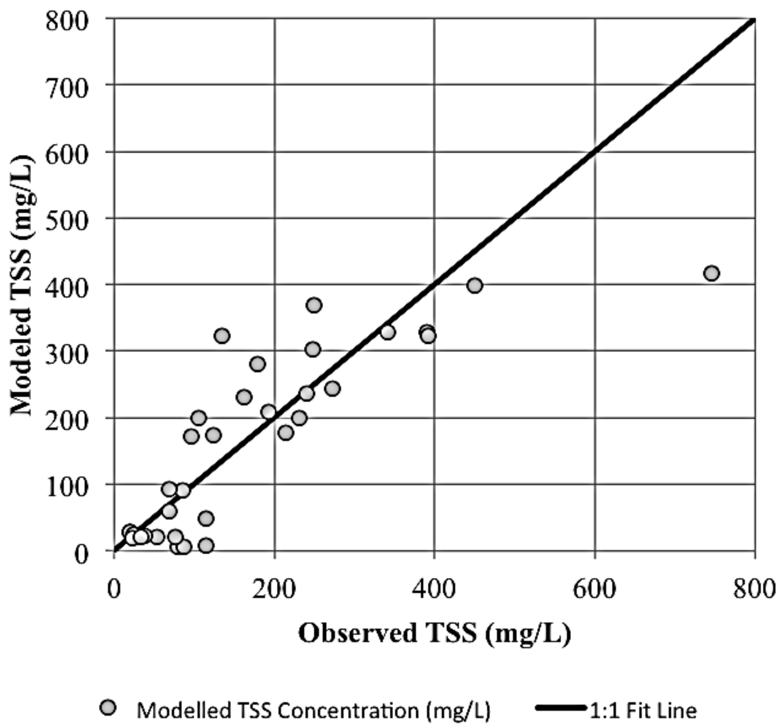

Figure 3 Comparison of all modelled TSS concentrations against observed values

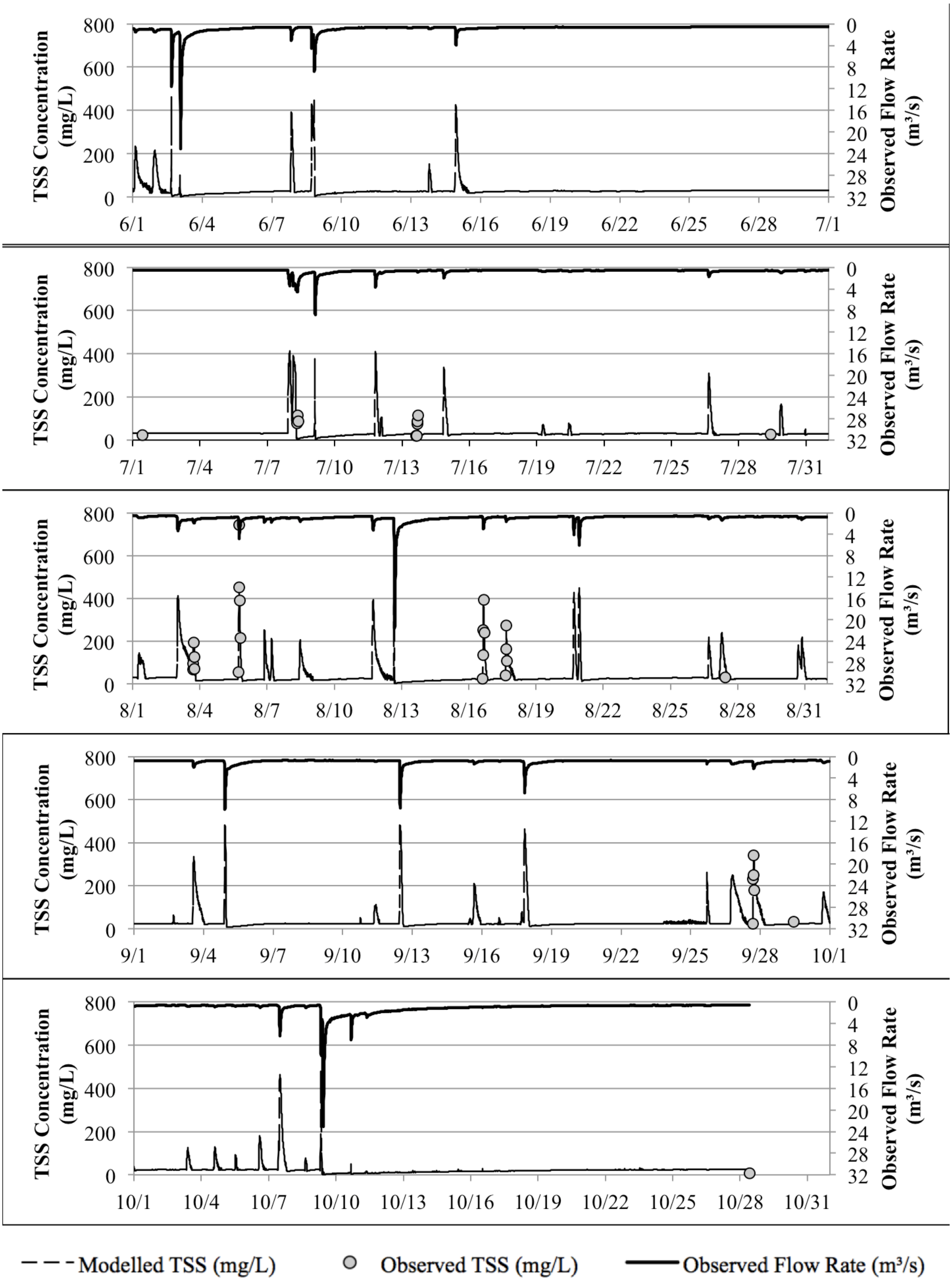

Figure 4 Continuous simulation of TSS concentrations used to estimate seasonal mass loading

4. Discussion

While the model estimated that the WWTP collected about 44% of the particulate matter, it should be noted this estimate is likely the maximum potential treatment capacity of the system. The estimate is based on the assumption that the pump house was pumping at full capacity (0.55 m^3/s) at all times. During heavy rainfall, however, a water gate is often closed to prevent excessive flows from entering the pump house. Additionally, power outages and mechanical malfunctions create system downtime. The uncertainty of the gate's actual opening and closing times prevented its inclusion in the model.

Furthermore, the model demonstrated some limitations in representing one observed peak concentrations during very intense rainfall. Therefore, it is possible that the model underestimates peak concentrations in high intensity rainfall. Because the peak concentration was observed once, it is uncertain whether that event was an outlier; Further investigation is needed.

Finally, the rainfall that occurred in 2015 was anomalously low (the lowest on record at a weather station within the municipality operated by the Royal Irrigation Department). Therefore, it is expected that average and above average years of precipitation would have higher seasonal loading of pollutants and much high flow volumes.

Overall, however, the model provides a representation of the combined sewer system's water quality that is appropriate for planning purposes while avoiding problematic over parameterization.

5. Conclusion

This study demonstrated the acceptable calibration (NSE = 0.74), validation (NSE = 0.54), and application of a parsimonious water quality model to the continuous simulation of TSS concentrations in a mid-size urban catchment in a tropical climate. The results of a continuous simulation provided an estimate of the total mass of TSS discharged through the system during the rainy season (June to October 2015) at 537,000 kg, with approximately 44% of that mass collected by the WWTP for treatment. They also estimate that the majority (63.4%) of particulate pollution mass is charged during wet-weather conditions, of which about a quarter (24.6%) is collected for treatment.

The results from this modelling exercise provide useful information to water resource and environmental planners in the city. Further research will seek to establish a rainfall-runoff model to couple with this water quality model, so that water quality can be estimated from rainfall data and not require continuous monitoring of water levels in the sewer system.

6. Acknowledgements

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