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Industrial Electrical Engineering and Automation

Towards a system-wide Benchmark Simulation Model

Catchment and sewer system modelling

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Summary

Integrated modelling has been a very useful tool to identify the interactions between different components of an urban wastewater system. Such models are being used to assess the performance and predict the benefits of applying integrated control using a holistic approach. The system-wide Benchmark Simulation Model represents an extension to the plant-wide BSM models and includes the catchment, sewer network and river models as well. The current report describes the catchment and sewer system components of the system-wide BSM. A hypothetical catchment and sewer system are described. The modelling approach for each of the individual components is presented in detail. An analysis of the results obtained using the catchment model to generate the wastewater flows, and, sewer system model to transport the generated flows to the wastewater treatment plant and/or river is performed. It provides an understanding of the behaviour of the hypothetical catchment under varying weather conditions. The knowledge obtained is essential for any future integrated control strategy development.

1. Introduction

The close interactions between catchment, sewer network, wastewater treatment plant (WWTP) and receiving water call for their (model-based) design and operation to be developed and evaluated in a holistic manner (**Benedetti et al., 2013**). Integrated control has been studied for many years and the main benefits of using such an approach are demonstrated in several scientific contributions (e.g. **Schütze et al., 2002; Vanrolleghem et al., 2005; Langeveld et al., 2013**). For this reason, the plant-wide benchmark simulation model no.2 (BSM2) (**Jeppsson et al., 2007; Gernaey et al., 2014**) is extended to include catchment, sewer network and receiving water models. This can provide a platform to assess the impact of integrated control strategies on different elements of the urban wastewater system (UWS).

The system-wide Benchmark Simulation Model (sBSM) consists of models for different sub-systems in the UWS. The plant-wide BSM2 model is used to describe various unit processes in the WWTP. A catchment model that describes the generation of flow rate and pollutants during both dry weather and rain periods is developed. The dynamic influent pollutant disturbance scenario generator (DIPDSG) (**Gernaey et al., 2011**) is used as the starting point to develop the catchment model. A sewer system model is built to simulate the transport of flow and different pollutants from the catchment to WWTP. Additionally, it can also simulate the discharge of wastewater and rainwater directly into the river through a sewer overflow. A river quality model based on the River Water Quality Model No. 1 (RWQM1) (**Reichert et al., 2001**) describes the influence of sewer overflows and WWTP discharges into the receiving media. The four components (catchment, sewer system, WWTP and river) are combined using interfaces to develop a system-wide model of the UWS. Therefore, a hypothetical system layout is developed. The benchmark model with its various control elements (sensors, actuators and controllers) can be used to simulate the effect of different control strategies (both integrated and local) on the performance of the sewer system, WWTP and more importantly on the quality of the river. This combined model can be a helpful tool to replace commonly used indirect evaluation criteria for UWS performance (based on quality of discharges from sewer overflows and WWTPs) with direct evaluation indices to determine the river water quality, which is also the ultimate aim of the indirect assessments. With the use of direct measures, the interactions between various components and their influence on the receiving water quality can be studied.

This report details the modelling approach for different building blocks in the catchment and sewer network models.

2. Catchment characteristics

A hypothetical catchment structure similar to the catchment described in ATV A 128 (**ATV, 1992**) case study is used. The catchment characteristics are scaled up to match BSM2 WWTP influent flow rate (20,650 m^3/d). **Figure 1** describes the catchment structure and the main characteristics of the catchment in terms of area, population equivalents (PE), domestic and industrial flow. It has a total area of 540 hectares and 80,000 population equivalents. Daily average domestic wastewater flow is 12,000 m^3/d. It also has an industrial sub-catchment with a daily average flow of 2,500 m^3/d. An average yearly infiltration of 4,850 m^3/d is assumed. Infiltration to sewers accounts for 25% of the dry weather flow. The catchment includes six sub-catchments (SC), each with different areas and population densities. SC1, SC2, SC3, SC4 and SC6 are connected to a combined sewer system whereas SC5 is connected to a separate sewer network. All the defined SCs are considered to be domestic except SC2, which has both domestic and industrial areas. The studied system has five storage structures (four online pass-through tanks and one offline bypass tank). The volume of each of these tanks is 30 m^3/ha of the catchment area connected to the storage tank. One of the online pass-through tanks is connected to the separate sewer system in SC5. The entire catchment is connected to a WWTP, which has the same layout/characteristics as the BSM2 plant-wide model (Jeppsson et al., 2007). Sewer overflows and WWTP effluents are discharged at various locations into the receiving waters as depicted in **Figure 1**. A receiving water system model based on RWQM1 (Reichert et al., 2001) was also developed, but will not be further discussed in this report.

3. Model description

The model description for the system-wide model can be subdivided into four broad sections:

1. Catchment;
2. Sewer network;
3. Wastewater treatment plant;
4. Receiving water system.

Models used to describe the catchment and sewer network are described in detail in the following sections.

Sub catchment	Area (ha)	PE	Wastewater flow (m^3/d)	
			Domestic (HH)	Industrial (IndS)
1	99	15920	2390	0
2	21	3920	590	2500
3	29	2960	440	0
4	71	9600	1440	0
5	71	7840	1180	0
6	249	39760	5960	0
Total	**540**	**80000**	**12000**	**2500**

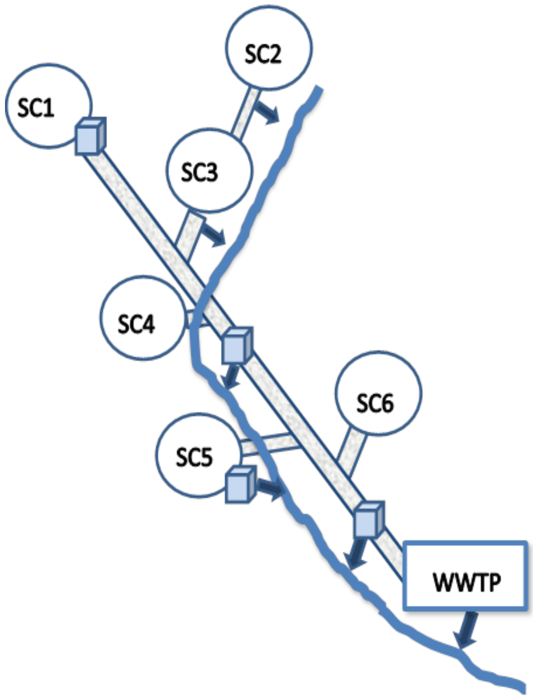


Figure 1: System-wide BSM layout and catchment characteristics.

3.1. Catchment

Modelling the urban catchment includes generation of pollutant loads and flow rate during dry weather and rain events. A yearly dry weather wastewater generation pattern was created. Additionally, the effect of any intermittent rain events was included. In addition to flow rate (m^3/d), pollutants included in the catchment model are chemical oxygen demand (*COD*), ammonium (NH_4^+), nitrate (NO_3^-) and phosphate (PO_4^{3-}). *COD* is further subdivided into *CODsol* (soluble *COD*) and *CODpart* (particulate *COD*). All pollutants are represented in loading terms (kg/d).

3.1.1. Dry weather pollutant loads and flow rate generation

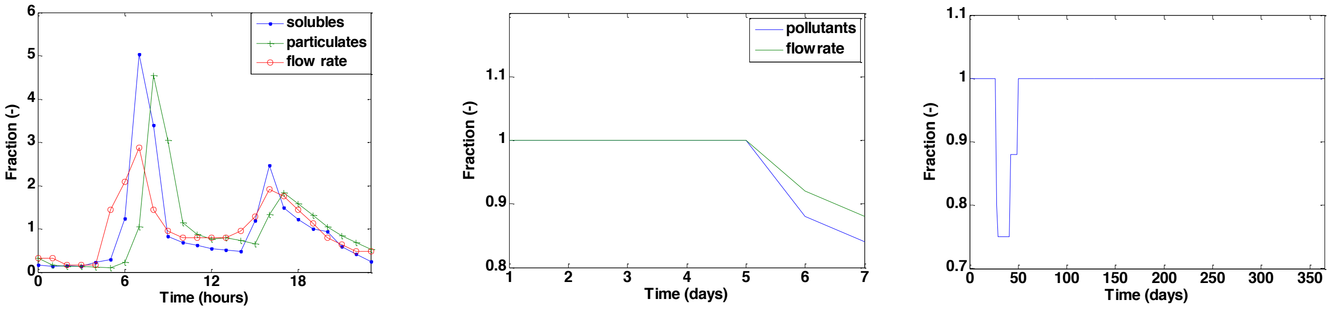
Generation of pollutants and wastewater flow during dry weather varies on a daily, weekly and yearly basis. The profiles also vary between domestic and industrial sections (see **Gernaey et al., 2011** for further details).

Domestic

The variation in domestic dry weather wastewater generation is modelled using three different profiles of varying time durations.

1. Normalized daily profile: A normalized diurnal profile (*domestic_day.mat*) for the variation of pollutant loads and wastewater flow is used to simulate the daily variation in wastewater flow and pollutant load generation. The profile has a morning peak and an evening peak. Night times have the lowest loads and flow due to low domestic wastewater generation during nights (**Figure 2a**). The profiles are different for solubles, particulates and flow rate. Particulate pollutant (*CODpart*) is transported at a slower velocity and has a delay of one hour in comparison to soluble pollutants.

2. Weekly profile: A drop in the pollutant generation during weekends is modelled using a weekly profile (*domestic_week.mat*) with a uniform value during weekdays and a lower load during the weekends (**Figure 2b**). The weekly profile is similar for all pollutants while flow rate has a slightly different behaviour.



a b c

Figure 2: Diurnal variation in pollutant loads and flow rate (a). Weekly variation with two different profiles (blue-pollutants, green-flow rate) (b) and yearly profile with similar dynamics for pollutants and flow rate (c).

3. Yearly profile (holiday effect): Additionally, it is possible to simulate a holiday period with lower domestic wastewater flows using the yearly profile (*domestic_year.mat*). The yearly profile has a constant value across the year except for a holiday period during which the flow rate and pollutant load drop by an equal factor (**Figure 2c**). The yearly profile begins on the 1st of July.

Industrial

Industrial wastewater generation is also modelled on the basis of a weekly and a yearly profile.

1. Weekly profile (*industrial_week.mat*): A weekly cleaning and maintenance period is simulated with a higher wastewater generation during every Friday and a weekend with reduced generation of wastewater is assumed (**Figure 3a**).

2. Yearly profile (*industrial_year.mat*): Two holiday periods marked with lower wastewater generation are modelled (**Figure 3b**). Same as in domestic profiles, the yearly industrial profile begins on 1st July.

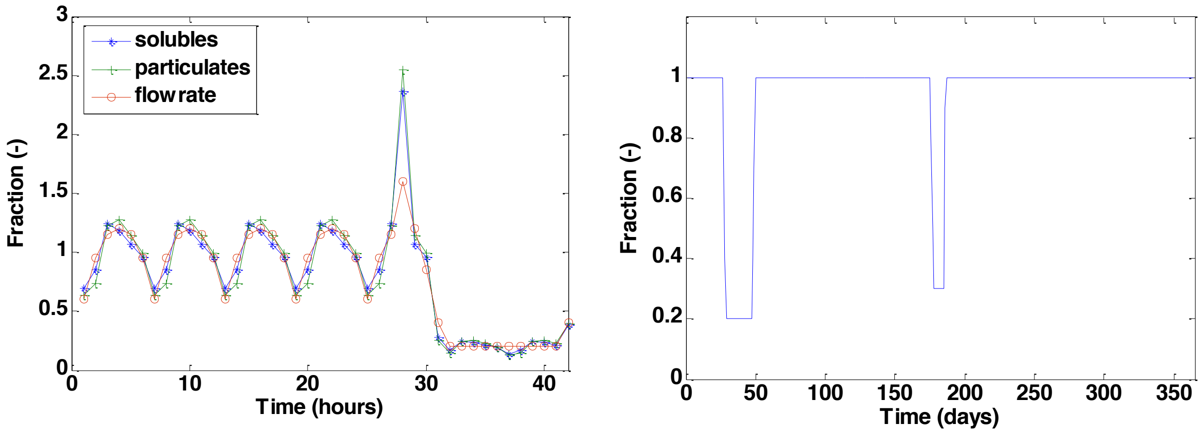


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Figure 3: Dynamics of industrial dry weather pollutant and flow rate generation with weekly (a) and yearly (b) variation.

For both the domestic and industrial sub-catchments, the profiles for daily, weekly and yearly variation are multiplied to generate an annual profile for pollutant load and flow variations. In the case of domestic sub-catchments, the annual profile is multiplied by: 1) the number of population equivalents (PE), and, 2) average loads (kg/PE.d)/flow rates (kg/PE.d) (*domestic_avg.mat*) to simulate the dynamics in yearly wastewater generation. The file domestic_avg.mat is a 1x6 matrix that contains the annual average values for pollutant loads and flow rate. A random number generator is also included in the model to make sure that the profiles are not too strongly correlated. For industrial catchments, the annual profile is multiplied with average values for loads and flow rate (kg/d and m^3/d) (*industrial_avg.mat*) to generate the annual industrial wastewater profiles. **Figures 4a,b** describe the variation in flow rate generated using the catchment dry weather model for domestic and industrial sub-catchments, respectively. An initial holiday period can be noticed for both the profiles. Also weekly and daily variations can be observed.

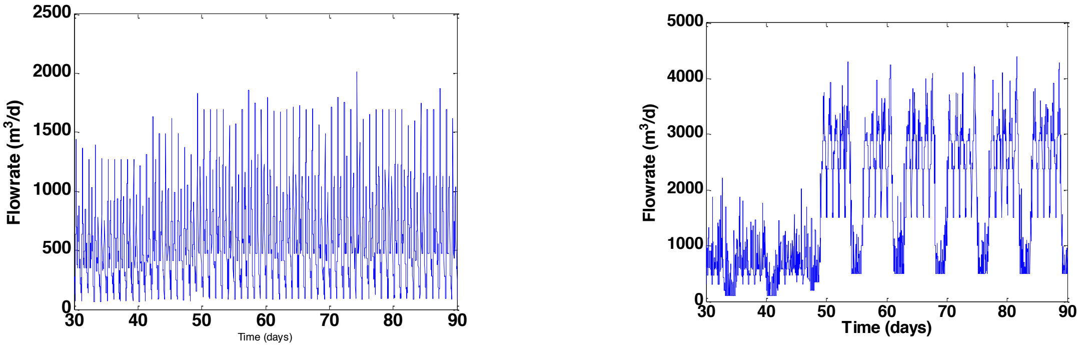

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Figure 4: The dry weather flow rate profile generated for a domestic sub-catchment with PE= 3,920 and daily average flow rate = 0.15 m^3/PE.d (a) and for an industrial sub-catchment (b) with a daily average flow rate of 2,500 m^3/d.

3.1.2. Wet weather modelling

Wet weather modelling includes models for generation of surface runoff due to rainfall. Also, rain events lead to wash-off of pollutants from the catchment surface to the sewer system. This phenomenon is included in the model.

Rainfall

Rainfall described as intensity (mm/h) is provided as an input to the model. Rainfall data with a frequency of 12 hrs is currently provided. The rainfall profile is characteristic of Scandinavian rainfall conditions (**Figure 5**).

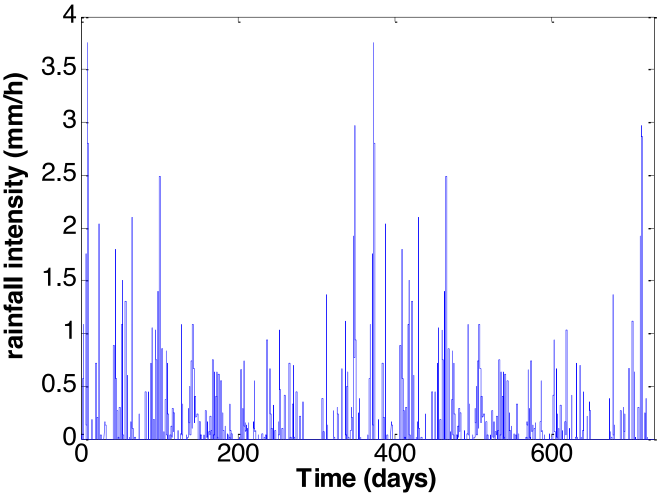


Figure 5: Rainfall intensity data used in the system-wide BSM model.

Rainfall runoff model

A rainfall runoff generation model is used to convert the rainfall intensity (mm/h) into surface runoff (m^3/d). The runoff model uses a dimensionless rainfall runoff coefficient (*rrc*) to represent various continuing losses taking place in the catchment. Rain falling on impervious areas (A_{imp}) is multiplied with the *rrc* to generate the runoff, which is then passed through a linear reservoir model to simulate the delay and attenuation in runoff typically observed in urban catchments. The linear reservoir model is similar to the one used in the sewer system and is described in Section 3.2.4.

Pollutant model

Generation of pollutants from the catchment during rain events is modelled differently for particulate and soluble pollutants.

Soluble pollutant – Event mean concentrations

A constant pollutant concentration is used to represent the soluble pollutant generation due to rain. Also known as event mean concentrations (EMC), these values vary based on catchment characteristics and rain event. Representative EMC values based on Butler and Davies (2000) are used for the case study (**Table 1**). Concentrations for nitrate and phosphate are assumed to be zero. The EMCs are denoted as *emc_codsol* and *emc_nh4* in the model. These concentrations are multiplied with the flow rate obtained from the rainfall runoff model to generate pollutant loads.

Table 1: Event mean concentrations (EMC) for soluble pollutants during rain envents.

Pollutant	EMC (g/m^3)
Soluble COD	9
Ammonium	0.56
Nitrate	0
Phosphate	0

Particulate pollutants - Pollutant accumulation and wash-off model

Particulate pollutants accumulate during dry weather periods until a maximum threshold is reached. During rain events, the accumulated pollutants are washed off depending on the intensity of the rain event and the amount of pollutants accumulated.

$$\frac{dM_s}{dt} = aA - bM_s - 24k_4 iM_s \qquad \textbf{Eq. 1}$$

The pollutant accumulation and wash-off model (**Equation 1**) describes the mass of a pollutant on the surface (M_s) (kg). A *surface accumulation rate constant* (a) (kg/ha.d) defines the rate of accumulation of the pollutant and the total accumulation is a product of a and *catchment area* (A). Inorder to avoid pollutant mass reaching large values, a removal rate characterized by the parameter b (*decay rate constant* (d^{-1})) is used. Hence, during a long dry period, a maximum pollutant mass is reached and no further accumulation takes place. During a rain event, the pollutant is washed at a rate determined by the *wash-off constant* (k_4) (mm^{-1}) and rainfall intensity (mm/h) and the available mass on the catchment surface. A conversion factor (24) is used to convert the resulting wash-off load from kg/h to kg/d.

Figure 6 describes the particulate pollutant model for rain events, during dry weather periods the pollutant initially accumulates at a faster rate and the rate of accumulation gradually decreases. With the onset of rainfall, the accumulated pollutant gets washed off depending on the intensity of the rain.

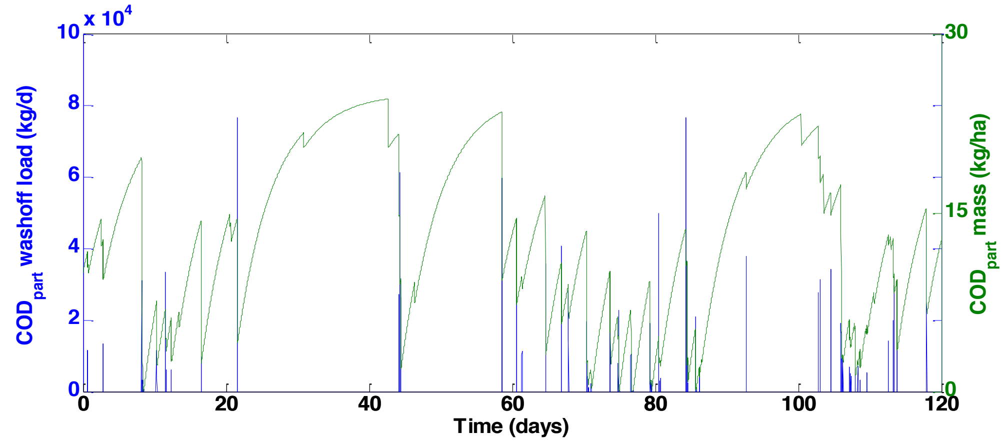
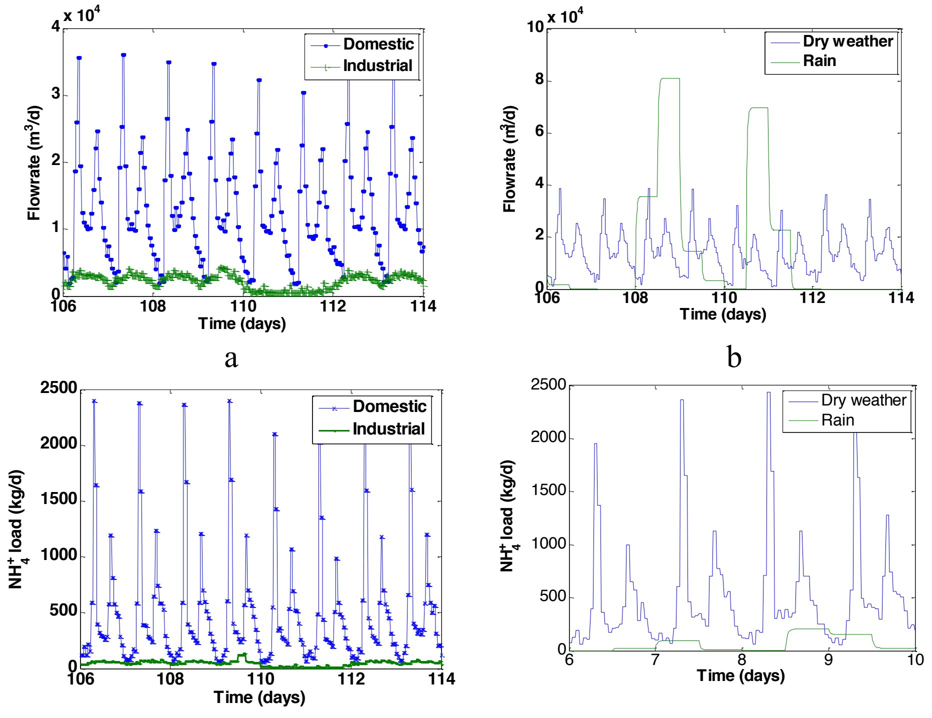


Figure 6: Particulate *COD* model for rain events describing the accumulation (blue) and wash-off (green) based on the accumulation and wash-off model described in equation 1.

Finally, the dry weather and wet weather models are combined to generate daily pollutant loads and flow from each catchment. For SC5, the rainwater is separated and reaches the river system. The profiles for a particular pollutant (NH_4^+) and flow rate for the entire urban catchment are depicted below (**Figure 7**). Contributions from domestic and industrial sources are represented in **Figures 7a,c**. Both plots show that during dry weather period, domestic sources are the major contributors compared to industries as only SC2 is an industrial catchment. During wet weather, additional flow and pollutant loads are generated (**Figures 7b,d**). Rain generated flow completely dominates the dry weather flow. In the case of pollutants, the EMCs of the pollutants are low when compared to the dry weather average concentrations. Hence, the impact of rain-generated pollutants is not as dramatic as that of the flow rate.



a b

c d

Figure 7: Dynamic variation in pollutant loads and flow rates generated from the catchment model including dry weather and rain events.

3.2. Sewer network

The generated wastewater and stormwater from the catchments are transported to the sewer system. The sewer network sub-system consists of the following model blocks:

1. Infiltration to sewers;
2. First flush model for particulates;
3. Storage tanks;
4. Sewer transport.

3.2.1. Infiltration to sewers

In addition to domestic and industrial flows, additional inflows to the sewers arise due to infiltration. It is assumed that 25 % of the dry weather inflow to WWTP is due to infiltration. Infiltration model currently used is similar to the soil model used in DIPDSG. The soil model is represented as a tank with storage capacity. The model has two inputs:

1. Seasonal groundwater inflow (*gw_in*);
2. Rainfall dependent inflow (*rdi_in*).

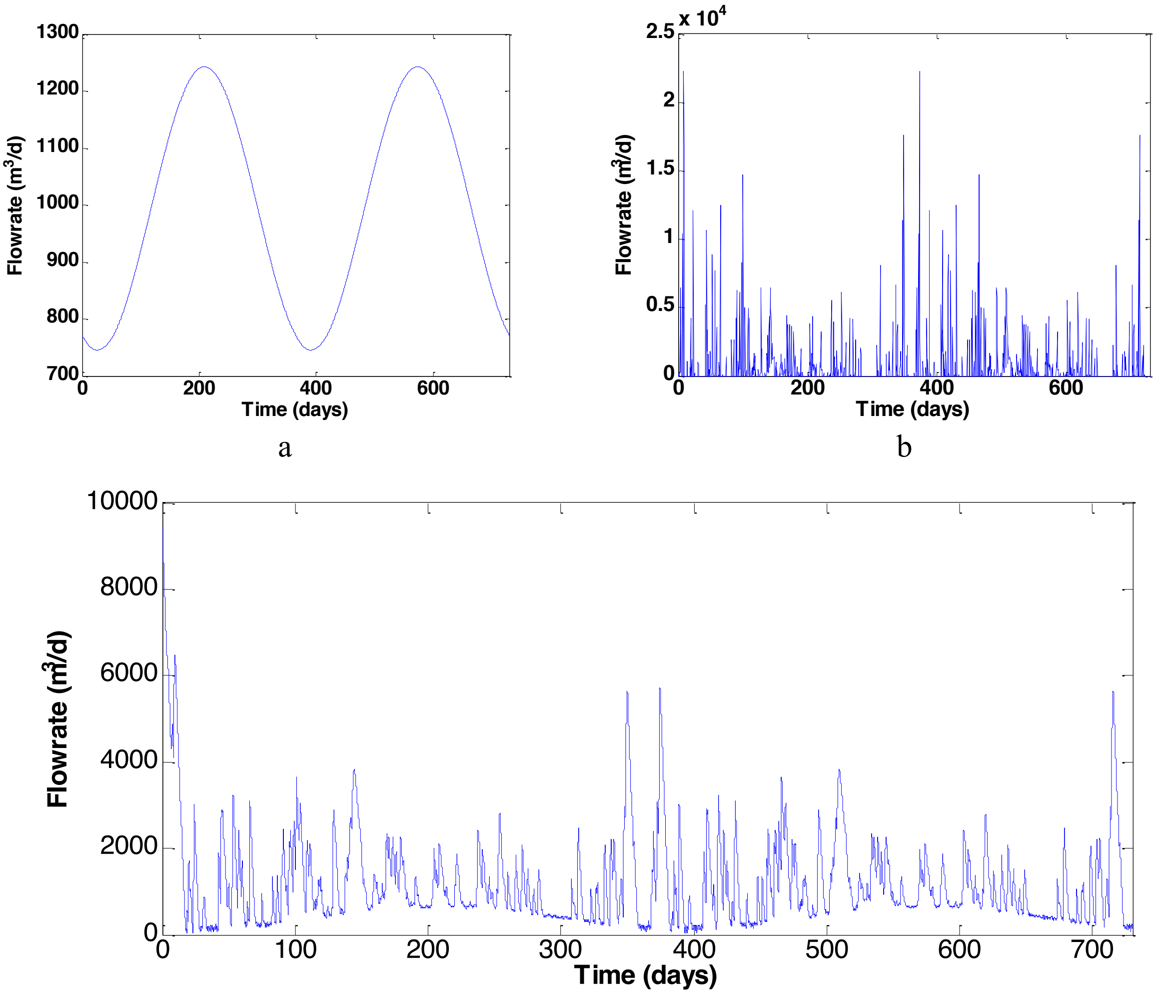
Seasonal groundwater inflow is modelled as a sine wave with a yearly frequency (**Figure 8a**). The groundwater inflow to the model is at its lowest during the dry period and at its highest during the rainy period of the year. The annual mean groundwater flow (*gwbias*) for the entire catchment is 7,100 m^3/d and the amplitude of variation (*amp*) is 25%. Based on the area of each sub-catchment, a mean groundwater inflow is defined as a fraction of the annual average for the catchment. Additionally, runoff generated due to rain from pervious areas (*rdi_in*) of the catchment is considered as an input to the model. A soil permeability parameter (K) is introduced. It determines the maximum amount of rain runoff that can percolate into the soil for a given area ($K*A$). Any excess rainfall runoff on pervious areas is sent to the sewer system as surface runoff. **Figure 8b** describes the runoff from pervious areas in SC1 reaching the soil model.

The combined inflow from these inputs is converted into storage volume for the tank represented by height (h) of the tank for a given area (A). This area is a model parameter. The following outputs from the tank are modelled as a function of the tank height:

1. Infiltration to sewers (*Qinf*);
2. Inflow to groundwater (*Qgw*).

$\frac{dV}{dt} = gw_{\text{in}} + rdi_{\text{in}} - Q_{\text{inf}} - Q_{\text{gw}}$	**Eq. 2**
$\frac{A.dh}{dt} = gw_{\text{in}} + rdi_{\text{in}} - K_{\text{inf}}.\sqrt{h - H_{\text{inv}}} - K_{\text{down}}.h$	**Eq. 3**

Infiltration to sewers from the soil model is modelled by parameter *Kinf*. Infiltration to sewers occurs only when the storage tank level is higher than *Hinv*. The maximum storage level is *Hmax*. Similarly, infiltration to groundwater is determined using the parameter *Kdown*. **Equation 2** represents the volume balance for the soil model. **Equation 3** elaborates the volume balance based on the relationship between various outflows and the storage height (h). **Figure 8c** describes the infiltration to sewers (*Qinf*) from the soil model. It can be seen that the effect of groundwater inflow and rainfall dependent infiltration can be noticed in the infiltration to sewers.



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b

Figure 8: Groundwater (a) and rainfall runoff (b) as inputs to the soil model in SC1. Output is the infiltration to sewers (c). Mean groundwater inflow is 994 m^3/d.

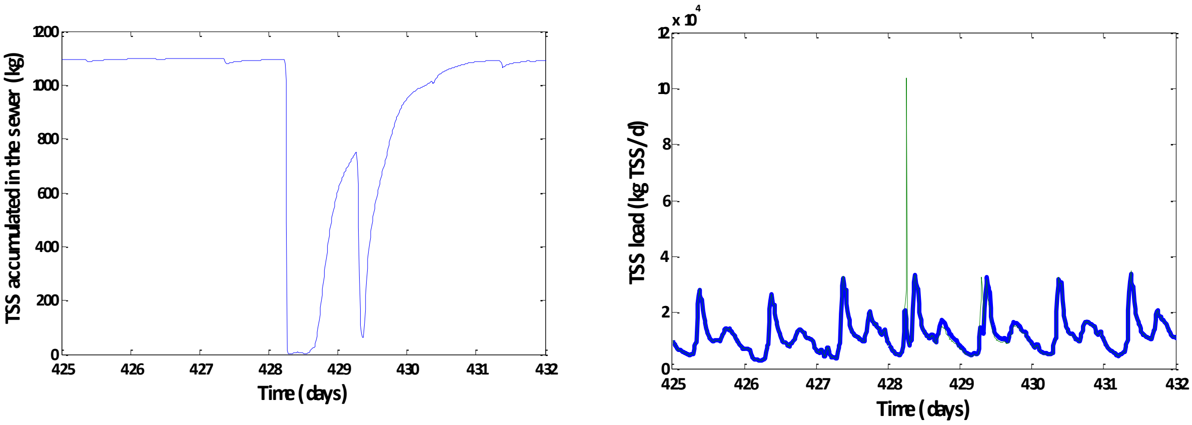
3.2.2. First flush model

For the simulation of high particulate loads observed at WWTP inlet during the beginning of rain events, a first flush model developed for DIPDSG is used here. A fraction of the daily generated particulate pollutants (*FFfraction*) is passed through the first flush model. During dry weather periods, the particulates accumulate until the threshold mass ($M_{\max}$) is reached. The accumulated particulates are washed off during rain events. The strength of wash-off depends on the intensity of the flow rate.

Equation 3 describes the accumulation of the total mass of solids in the sewer as a function of the flux of solids that is entering (M_{in}) and leaving (M_{out}) the system. Q_{in} represents the influent flow rate (m^3/d), TSS_{in} represents the suspended solids concentration that forms the input to the model, M_{max} (kg) is the maximum amount of particulates that can be stored in the sewer system. Q_{lim} (m^3/d) is the flow rate limit triggering the first flush effect, and FF (d^{-1}) and n (-) are adjustable parameters to tune the desired strength of the first flush effect.

$\frac{dM}{dt} = TSS_{\text{in}}\left(1 - \frac{M}{M_{\text{max}}}\right) - \frac{Q_{\text{in}}^{\text{n}}}{Q_{\text{lim}}^{\text{n}} + Q_{\text{in}}^{\text{n}}} . M.FF$	**Eq. 3**

Figure 9 depicts the influence of the first flush model on the sewer particulate pollutant behaviour. A fraction of the particulates keeps accumulating until the maximum threshold mass is reached. Any rain event will trigger wash-off of the pollutants (**Figure 9a**). The effect of the model can be clearly seen is **Figure 9b** with the inflow to the model (blue) and model output (green). A strong first flush effect is observed in this case owing to high rainfall intensity and large volume of mass accumulated in the sewer system. Such first flush models are present at different locations in the system-wide BSM to simulate the additional particulate pollutant loads during rain events.



a b

Figure 9: Accumulation and wash-off of TSS in the sewer system (a), effect of first flush on sewer inflow (blue) and outflow (green) TSS load (b).

3.2.3. Storage tanks

Storage tanks act as buffers to prevent discharge of rainwater into rivers during rain events. These tanks are also the main control elements to regulate the incoming flow to the WWTP and sewer overflows to rivers. Four different configurations of the tanks, which are classified into online and offline modes, are modelled (**Figure 10**).

1. Online tanks: These tanks are in-line with the sewer network and the storage tank is in use during dry weather as well. All dry weather flow passes through the tank and reaches the WWTP. Valves can be used to limit the throttle flow. A valve model with a linear relationship between valve opening and flow rate variation is included in the model.

2. Offline tanks: These storage tanks are not directly in-line with the sewer network. The sewer pipes have a maximum capacity and any excess flow reaches the storage tank. Hence, the dry weather flow does not reach such storage tank. In the case of offline tanks, typically pumps are used to send the stored wastewater back to the sewer system. Hence, outflow from the tanks is governed by the pumping rate. Pump flow can either be supplied as an input or as an actuator setting from a controller.

Pass-through and bypass configurations are modelled for both online and offline storage tanks.

1. Pass-through tanks: The overflow weir is located at the end of the storage tank. All the inflow to the storage tank passes through it before reaching the outlet or overflowing into the river.

2. Bypass tanks: These are tanks with the overflow at the beginning of the storage tank. This is advantageous especially in systems with high first flush effects as the first load of highly polluted wastewater is stored in the tank and any excess stormwater overflows. For online tanks, this highly polluted stormwater reaches the WWTP. Similarly, for offline tanks the stored stormwater can later be pumped back to the trunk sewer and from there reach the WWTP.

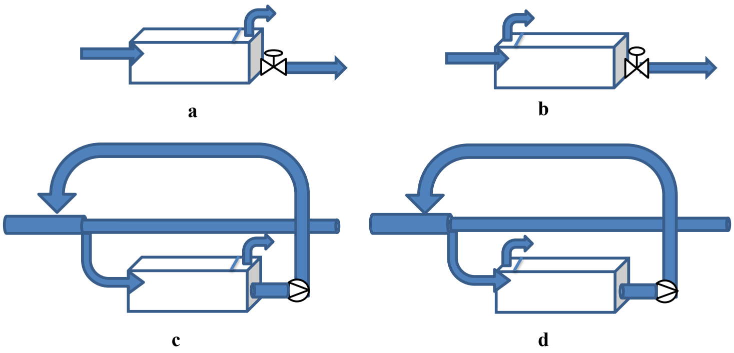


Figure 10: Different configurations of storage tanks: a) online pass-through tank; b) online bypass tank; c) offline pass-through tank; d) offline bypass tank. Pumps and valves are used as flow control elements in offline and online tanks, respectively.

$Q_{\mathrm{throttle}} = \dfrac{Q_{\mathrm{max}}(h - h_{\mathrm{min}})^{\mathrm{n}}}{h_{\mathrm{o}}^{\mathrm{n}} + (h - h_{\mathrm{min}})^{\mathrm{n}}}$	**Eq. 4**
$Q_{\mathrm{overflow}} = C.L_{\mathrm{weir}}.(h - h_{\mathrm{overflow}})^{1.5}$	**Eq. 5**

The throttle flow (Q_{throttle}) (m^3/d) and overflow (Q_{overflow}) (m^3/d) are described by **Equations 4 (Vallet, 2011)** and **5 (Hager, 2010),** respectively. Q_{max} is the maximum throttle flow (m^3/d), h_{o} is the height in the storage tank (m) when $Q=Q_{\mathrm{max}}/2$, h_{min} is the minimum water level in the tank (m), h is the water level in the tank (m), C is a constant for weir overflow, L_{weir} is the length of the weir (m) and h_{overflow} is the height of the overflow weir measured from the bottom of the tank (m).

Table 2 summarizes the mass balance and equations used for various storage tanks described in the system-wide BSM. Q_{in} and Q_{out} represent the inflow and outflow from the storage tanks. V is the volume of the tank filled with water and A denotes the surface area of the tank. In the case of online tanks, Q_{out} includes Q_{throttle} and Q_{overflow} while it includes Q_{pump} and Q_{overflow} for offline tanks. Q_{pump} is the pumping rate at which the stored water from an offline tank is sent back to the sewer system. M_{i} denotes the mass of each pollutant (i) and X_{i} represents the corresponding inflow load for the pollutant.

Table 2: Summary of modelling details for various storage tank models used in the system-wide BSM.

		Online		Offline	
		pass-through	bypass	pass-through	bypass
Mass balance	Volume	$\frac{dV}{dt} = \frac{1}{A}(Q_{\text{in}} - Q_{\text{out}})$	$\frac{dV}{dt} = \frac{1}{A}(Q_{\text{in}} - Q_{\text{out}})$	$\frac{dV}{dt} = \frac{1}{A}(Q_{\text{in}} - Q_{\text{out}})$	$\frac{dV}{dt} = \frac{1}{A}(Q_{\text{in}} - Q_{\text{out}})$
	Mass	$\frac{dM_{\text{i}}}{dt} = X_{\text{in}} - \frac{Qout}{V}.M$	$\frac{dM_{\text{i}}}{dt} = X_{\text{in}} - M_{\text{i}}.\frac{Q_{\text{throttle}}}{V} - X_{\text{in}}.\frac{Q_{\text{overflow}}}{Q_{\text{in}}}$	$\frac{dM_{\text{i}}}{dt} = X_{\text{in}} - \frac{Qout}{V}.M$	$\frac{dM_{\text{i}}}{dt} = X_{\text{in}} - M_{\text{i}}.\frac{Q_{\text{throttle}}}{V} - X_{\text{in}}.\frac{Q_{\text{overflow}}}{Q_{\text{in}}}$
Throttle/ pump	Flow rate	$Q_{\text{throttle}}(Eq.6)$	$Q_{\text{throttle}}(Eq.6)$	Q_{pump}	Q_{pump}
	Loads	$M_{\text{i}}.\frac{Q_{\text{throttle}}}{V}$	$M_{\text{i}}.\frac{Q_{\text{throttle}}}{V}$	$M_{\text{i}}.\frac{Q_{\text{pump}}}{V}$	$M_{\text{i}}.\frac{Q_{\text{pump}}}{V}$
Overflow	Flow rate	$Q_{\text{overflow}}(Eq.7)$	$Q_{\text{overflow}}(Eq.7)$	$Q_{\text{overflow}}(Eq.7)$	$Q_{\text{overflow}}(Eq.7)$
	Loads	$M_{\text{i}}.\frac{Q_{\text{overflow}}}{V}$	$X_{\text{in}}.\frac{Q_{\text{overflow}}}{Q_{\text{in}}}$	$M_{\text{i}}.\frac{Q_{\text{overflow}}}{V}$	$X_{\text{in}}.\frac{Q_{\text{overflow}}}{Q_{\text{in}}}$

Figure 11 presents the behaviour of online (a) and offline (b) storage tank models for a given input flow rate. In the case of online tanks the throttle flow varies based on the tank volume whereas it is fixed at a given maximum flow for offline tanks. The pumps are modelled in a way that they turn on only during periods when there is no inflow to the offline storage tank.

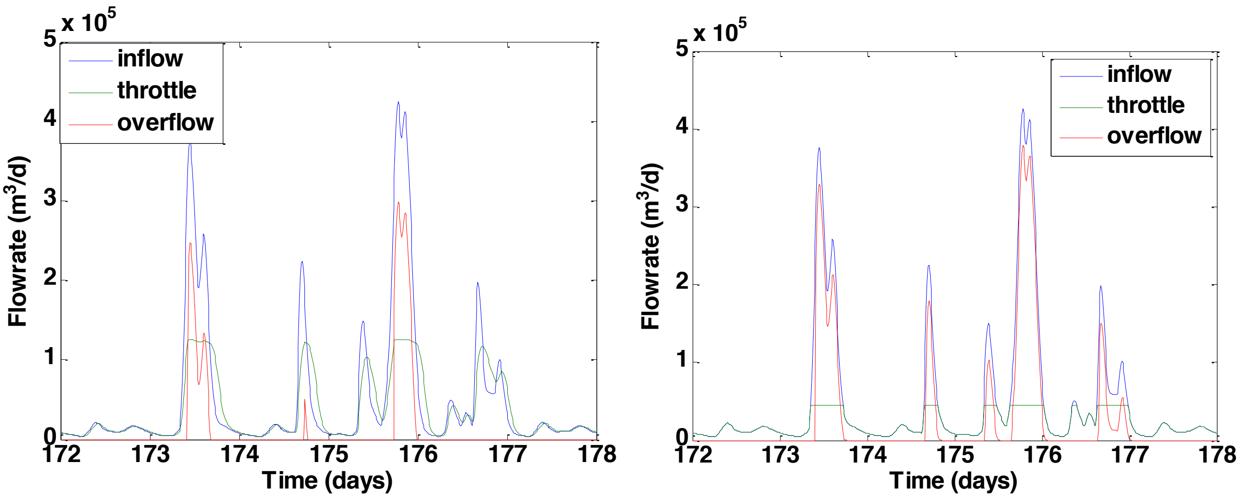


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Figure 11: Modelling of online (a) and offline (b) storage tanks for a give inflow.

For online tanks, the throttle flow can also be restricted with valves. Valve opening can be specified either as a user input or as an input from the controller. The throttle flow varies linearly with valve opening.

3.2.4. Sewer transport

The transport in the sewer system is modelled using linear reservoir models (Viessman et al., 1989). A series of linear reservoir models are used. The number of such linear reservoir models in series depends on the size of the upstream catchment. The larger the upstream catchment is, the higher is the number of reservoirs in series.

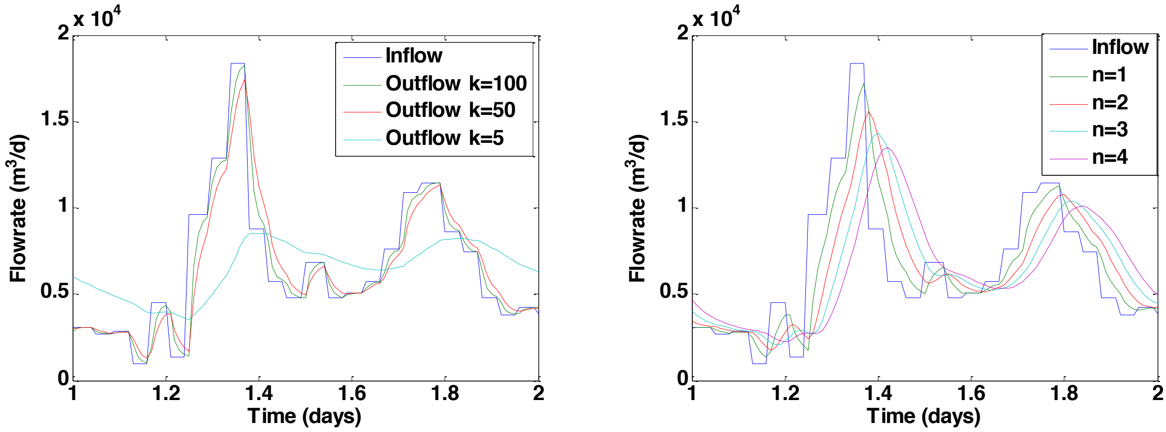
Each reservoir is modelled as a tank with varying volume. The output from the tank is a function of the storage volume.

$\frac{dV}{dt} = Q_{\text{in}} - Q_{\text{out}};\ V = \frac{1}{K} Q_{\text{out}}$	**Eq. 6**
$\frac{dM}{dt} = X_{\text{in}} - X_{\text{out}};\ M = \frac{1}{K} X_{\text{out}}$	**Eq. 7**

Equation 6 represents the mass balance for volume (V) (m^3) where Q_{in} and Q_{out} are input and output flow rates (m^3/d), respectively. The flow rate to load ratio is related to the mass accumulated based on a residence time constant (*1/K*) (d). Similarly, in **Equation 7**, M is the pollutant mass (kg). X_{in}, X_{out} are the input and output loads (kg/d).

Modelling such reservoirs in series is done using the same approach as used in DIPDSG (Gernaey et al., 2011). The number of such reservoirs to be used can be determined using a parameter n (integer ranging from 1 to 4).

Figure 12 presents the effect of linear reservoir models. The output from the reservoir model is delayed and attenuated depending on the residence time (**Figure 12a**). The effect of the number of sub-areas on the output flow rate is depicted in **Figure 12b**.



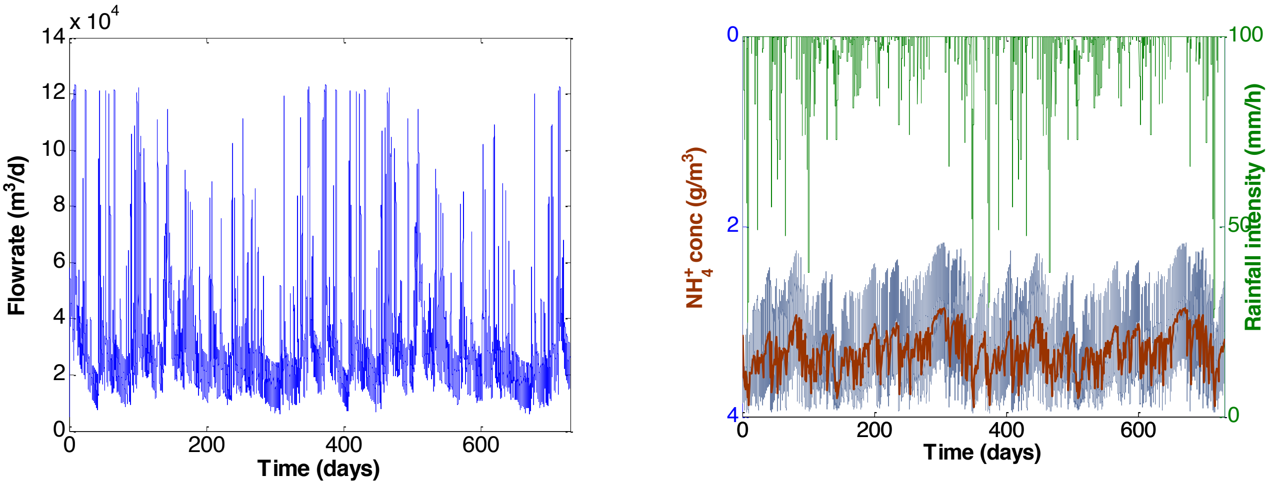
a

b

Figure 12: Reservoir model used for the sewer network. Effect of different residencence time constants (1/K) for a given inflow (a). Variation in the outflow based on the number of such reservoirs in series (b).

3.3. Catchment & sewer extension – Analysis

The inflow to sewer system from the catchment model combined with the infiltration flow pass through the sewer network and storage tanks to reach either the WWTP or the river. The inflow to the WWTP is highly dynamic with variation during dry weather and a more significant variation due to intermittent rain events (**Figure 13a**). Pollutant concentrations vary dynamically on a daily basis based on the profiles for domestic and industrial catchments. During rain events, a dilution in the pollutant concentration can be observed. **Figure 13b** represents the ammonia concentrations (with daily mean values in red) at WWTP inlet. From the daily mean value trend, a dilution in concentration can be observed during rain events. This is due to dilution of the dry weather pollutant load with less polluted storm flow.



a b

Figure 13: Flow rate a) and ammonia (b) simulation results at WWTP inlet.

Table 3 details the overflow statistics in terms of volume, duration and frequency of the overflows. The results are averaged annul values from a 2 year evaluation period. It should be noted that SC5 is a separate sewer system and hence all the stormwater flow reaches the river system and consequently the relatively high overflow volume. In principle, every rain event at SC5 will result in a discharge to the river system. SC2 and SC3 discharge 45,350 m^3 and 50,600 m^3 only in spite of 33 and 22 annual combined sewer overflow (CSO) events respectively. It is due to the fact that SC2 and SC3 are the smallest sub catchments with an area of 21 ha and 29 ha respectively. Even with only 12 combined sewer overflow (CSO) events, SC6 discharges 235,700 m^3 of CSO as it is located downstream in the catchment (close to the WWTP) and also has the largest area 249 ha. In terms of the annual volume discharged, various sub catchment discharge locations can be arranged in descending order as SC5 > SC6 > SC4 > SC1 > SC3 > SC2.

Table 3: Frequency, duration and volume of overflows at different overflow locations.

	Overflow1	Overflow2	Overflow3	Overflow4	Overflow5	Overflow6
Frequency ($year^{-1}$)	14	33	22	17	106	12
Duration (h)	6.0	13.2	10.7	7.9	150.3	4.8
Volume (m^3)	119,050	45,350	50,600	125,000	588,100	235,700

Figure 14 presents annual pollutant load for various pollutant discharges to the river based on the overflow location. Also, the number of overflow events at each location is depicted. As SC5 is a separate sewer system, the overflow is arising only from rain events. Soluble COD load is higher in comparison to other overflow locations but the particulate COD and ammonia loads are in the same order of magnitude as other CSO locations. This is due to the fact that a CSO consists of pollutant loads from both domestic/industries as well as rain events whereas an overflow for a separate sewer system consists of pollutants arising only due to rainfall runoff. Pollutant loads for SC1, SC2 and SC5 have similar pollutant discharges. SC3 has the lowest discharge loads and SC6 the highest (except for COD soluble for which SC5 has the highest loads). Factors affecting the annual loads include catchment location (upstream vs downstream), catchment type (domestic vs industrial), catchment area and storage tank capacity etc.

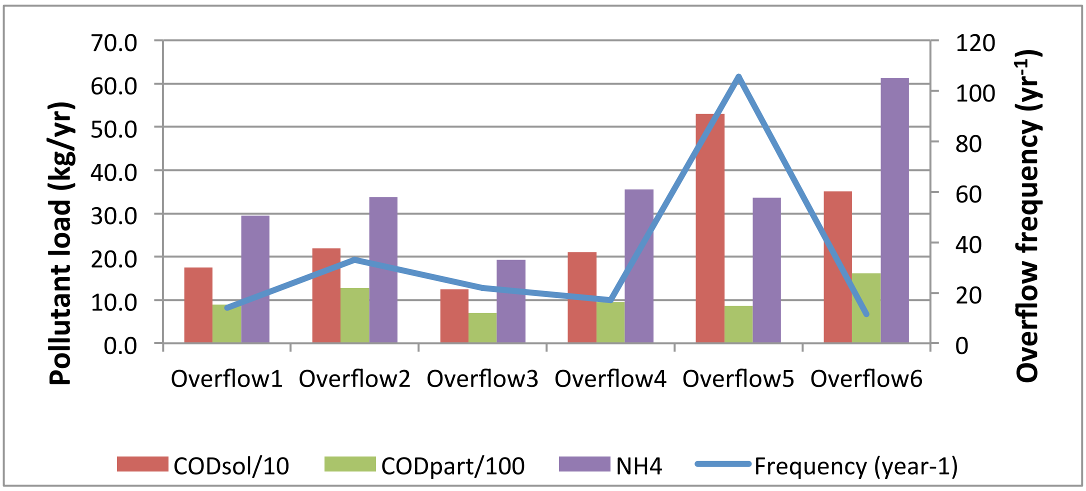


Figure 14: Annual pollutant loads and number of overflow events at different overflow locations.

4. Conclusions

The catchment and sewer network models presented in this report consider the major processes affecting wastewater generation from an UWS and include them in the overall BSM model. The model includes variation in dry weather wastewater generation due to both domestic and industrial sources. It also considers the effect of rain events on both flow rate and pollutant load dynamics. The sewer network model presented can simulate the major processes in the sewer network that affect the dynamic behaviour of wastewater/stormwater at the WWTP inlet and at overflows to the river. The sewer network model includes storage tanks that can simulate the overflows to rivers. These storage tanks combined with models for actuators (valves/pumps) can be used as control elements for both local and integrated control strategy analysis. In total, the catchment and sewer extension can be used to evaluate the behaviour of the catchment and sewer network during rain events and predict its impact on the WWTP and receiving waters. It is further coupled with the WWTP and river models to develop a system-wide model that can be used for integrated analysis and control of UWS.

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Appendix A

Table A.1. Main parameters for the catchment & sewer system extension

Model section	Parameter	Value	Units	Remarks
Domestic	*QperPE*	0.15	m^3/PE.d	Domestic wastewater flow rate per population equivalent
	PE	80	1000 PE	Population equivalents
	domestic_avg	19.31 115.08 5.8565 0 0	(kg poll/PE.d)	Average daily pollutant loads per PE for CODsol, CODpart, NH_4, NO_3, PO_4
Industrial	*QInd_weekday*	2 500	$m^3.d^{-1}$	Daily average wastewater flow rate from industry on normal week days (Monday to Thursday)
	industry_avg	386.24 2301.8 52.0625 0 0	kg poll/d	Average daily pollutant loads for CODsol, CODpart, NH_4, NO_3, PO_4
Rainfall runoff	*rrc*	1	-	Rainfall runoff coefficient to account for the continuing losses
	imp_frac	0.75		Impervious area as a fraction of total area
Pollutant accumulation and wash-off	*a*	5	$kg/m^2.s$	surface accumulation rate
	b	0.2	1/s	Decay rate constant for the pollutant accumulation model
	k4	0.3	mm-1	Wash-off constant
	emc_codsol	9	g/m^3	EMC for CODsol
	emc_nh4	0.56	g/m^3	EMC for NH_4
surface runoff	*kreservoir*	50	1/d	Reservoir time constant for surface runoff model
Infiltration	InfBias	4 850	m3.d-1	Mean yearly infiltration. Values for each SC are a fraction of InfBias.
	InfAmp	25	%	Amplitude of the sine wave
	InfFreq	$2 \cdot \pi/365$	$rad.d^{-1}$	Frequency of the sine wave (1 year)
	InfPhase	$\pi \cdot 15/24$	rad	Phase shift
Sewer	*n*		-	Number of sub-areas in the sewer system. Depends on the size of upstream SC.
	ksewer	50	1/d	Time constant for each sewer tank
First flush (parameters adjusted manually, vary for each first flush model)	*FFfraction*	0.25	-	Fraction of TSS that can settle in the sewer system
	Q_{lim}		$m^3.d^{-1}$	Limit flow rate triggering a first flush effect
	n		-	Exponent for Hill function
	M_{max}		kg	Maximum sediment mass stored in sewer system
	FF		d^{-1}	Gain for first flush effect
Storage tanks (values for some parameters vary for each storage tank)	A_{CSO}		m^2	Area of storage tank. Depends on the connecting upstream catchment. Calculated based on a storage tank volume of $30m^3$/ha of upstream area divided by H_{overflow}
	C		-	Varies. Tuned manually
	Q_{max}		m^3/d	Maximum throttle flow. 15*upstream average domestic flow.
	H_o	2.5	m	Height at which $Q=Q_{\mathrm{max}}/2$
	B	1	-	Hill function tuning parameter.
	H_{overflow}	5	m	Height above which overflow occurs
	L_{weir}	3	m	Length of overflow weir
	level	2	m	Minimum level in the tank at which pumping stops (offline tanks only)
	Q_{throttle}		m^3/d	Throttle flow (offline tanks only)
	pump		m^3/d	Pumping flow rate

Appendix B

Table B.1: List of files used in the catchment & sewer extension

Filename	File description
domestic_day	Normalized diurnal profile for domestic wastewater flow
domestic_week	Weekly profile for domestic wastewater flow
domestic_year	Yearly profile for domestic wastewater flow
industrial_week	Weekly profile for industries
industrial_year	Yearly profile for industries
domestic_avg	Average pollutant load (kg poll/PE.d) and flow rate (m^3/PE.d) for domestic flow
industrial_avg	Average pollutant load (kg poll/d) and flow rate (m^3/d) for domestic flow
rainfall_lynetten	Input rainfall data with 1 min frequency
reservoir_flow.c	S-function for surface catchment runoff linear reservoir model (Only flow)
rainpollutantmodel.c	S-function for catchment pollutant accumulation and wash-off model
reservoir.c	S-function for sewer linear reservoir model
firstflush.c	S-function for first flush model in the sewer system
storage_online_passthrough.c	S-function for online passthrough storage tank
storage_online_bypass.c	S-function for online bypass storage tank
storage_offline_passthrough.c	S-function for offline passthrough storage tank
storage_offline_bypass.c	S-function for offline bypass storage tank
influent_init_catchmentBSM	Initialization file for the catchment & sewer BSM extension