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System-wide Benchmark Simulation Model for integrated analysis of urban wastewater systems

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Introduction
Interactions between different components (sewer, wastewater treatment plant (WWTP) and river) of an urban wastewater system (UWS) are widely recognized (**Benedetti et al., 2013**). This has resulted in an increasing interest in the modelling of the UWS. System-wide models take into account the interactions between the different subsystems and allow us to operate the UWS in a holistic manner. Such an integrated approach makes it feasible to evaluate control strategies at an UWS scale with the aim of improving receiving water quality.

Currently, benchmark simulation models are widely used to evaluate local and plant-wide control strategies in WWTPs (**Jeppsson et al., 2013**). The International Water Association (IWA) Benchmark Simulation Models (BSM1, BSM1_LT, BSM2) consist of a predefined plant layout, process models, sensor and actuator models, influent characteristics and evaluation criteria (**Gernaey et al., 2014**). Given the success of BSMs in evaluation of control strategies for WWTPs, it is envisioned to spatially expand the plant-wide BSM to a system-wide tool. A system-wide BSM can then play an important role, not only in the evaluation of integrated control strategies, but also in developing a better understanding of the interactions between different components of an UWS.

This paper aims at presenting a system-wide benchmark simulation model that includes catchment, sewer network, WWTP and receiving water subsystems. A hypothetical UWS layout is defined and an integrated model for this system is developed. Modelling details for various building blocks of the model are explained in the following sections of this abstract. Preliminary simulation results are used to evaluate the impact of rain events using indirect (emission measures from sewers and WWTPs) and direct (river quality based) measures. We demonstrate the need of using a holistic approach due to the strong interactions between the elements of the UWS (catchment, WWTP and sewer).

Methodology
1. System layout
The catchment described in the ATV A 128 case study (**ATV, 1992**) is scaled up to meet the BSM2 population equivalents and total dry weather flow (**Saagi et al., 2014**). It consists of six sub catchments (five of them with a combined sewer system and one with a separate sewer system). The sewer network has five storage structures (combined sewer overflows (CSOs), online storage tanks, bypass tanks etc.). The catchment is connected to a WWTP, which in this case is the BSM1-ASM2d model (**Flores-Alsina et al., 2012**). The river system is modelled using a series of tanks each representing a stretch of the river system. A simplified version of the River Water Quality Model no. 1 (RWQM1) is used to describe the biological processes taking place in the river (**Reichert et al., 2001**). CSOs and effluent from the WWTP are discharged into the river at different locations. A graphical representation of the UWS is presented in Fig 1.

2. Models
Catchment
The dynamic influent pollutant disturbance scenario generator (DIPDSG) is used as the starting point for generating influent flow and pollutant loads from the catchment (**Gernaey et al., 2011**). Chemical oxygen demand (COD) is described using two fractions: soluble and particulate. Additionally, ammonium (NH_4^+), nitrate (NO_3^-) and phosphate (PO_4^{-3}) concentrations are described. Flow and

pollutant loads from the catchment are generated using daily, weekly and yearly profiles. The profiles vary between domestic and industrial catchments. During rain events, additional pollutant loads and flow are generated. Rainfall on impervious areas is converted to flow rate after subtracting losses (modelled using a rainfall runoff coefficient). For soluble pollutants, constant concentration values are used. In case of particulate pollutants, a pollutant accumulation and wash-off model is used. The wet weather flow is passed through a linear reservoir model to simulate surface runoff, which is then combined with the wastewater flow before reaching the sewer system.

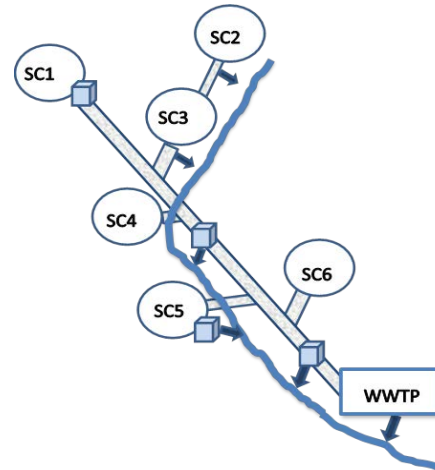| Sub catchment	Area (ha)	PE	Wastewater flow (m^3/d)	
			Domestic (HH)	Industrial (IndS)
1	99	15920	2390	0
2	21	3920	590	2500
3	29	2960	440	0
4	71	9600	1440	0
5	71	7840	1180	0
6	249	39760	5960	0
Total	**540**	**80000**	**12000**	**2500**

Figure 1: Catchment characteristics of the system-wide BSM (left), extended BSM2 catchment and sewer system layout (right).

Sewer system

The sewer network is modelled using a series of linear reservoirs that transfer the generated flow to the WWTP. Infiltration from soil into sewers is also included. Another essential feature of the sewer network, especially in the context of control, is the storage tank. Different possible configurations for storage tanks are modelled. Storage tanks also include valves and pump models. These act as actuators for the control elements.

WWTP

In this preliminary version, the sewer system is connected to a BSM1-ASM2d implementation of the WWTP. The N and P removal plant consists of seven reactors in series (two anaerobic, two anoxic and three aerobic) and one secondary sedimentation tank. Additional information about the design / operational conditions can be found in Flores-Alsina et al. (2012).

River

The simplified RWQM1 (Reichert et al., 2001) describes the dynamics of organic pollutants, nutrients and biomass in the bulk water phase of the river. The RWQM1 is developed in order to facilitate easy integration with the ASM family of WWTP models. The simplified version currently implemented consists of 19 state variables and 17 processes. The river system hydraulics is modelled using a series of varying volume tanks.

Interfaces

Interfaces are required to connect different sections of the system-wide model. To connect the sewer system with the WWTP, an existing sewer-ASM2d interface developed as a part of DIPDSG is used (Gernaey et al., 2011). An additional interface to connect WWTP effluent (ASM2d) to the river (RWQM1) is developed. The interface is based on the principles stated in (Nopens et al., 2009). Sewer discharges are connected to the river using sewer-ASM2d followed by ASM2d-river interfaces. All the interfaces ensure COD, C, N and P mass balances across the system.

3. Results

Fig 2 describes the dynamics of the wastewater inflow generation. The diurnal variation of domestic wastewater generation (a) and industrial flow (b) are presented. Contribution of domestic flow, industries and infiltration to the dry weather inflow to the WWTP is described (c). Domestic flow is the major contributor, followed by infiltration and industries. Influence of rain events on the inflow to the WWTP is described in (d). The contribution to the WWTP inflow from dry weather flow is dominated completely by rain generated inflow during wet periods.
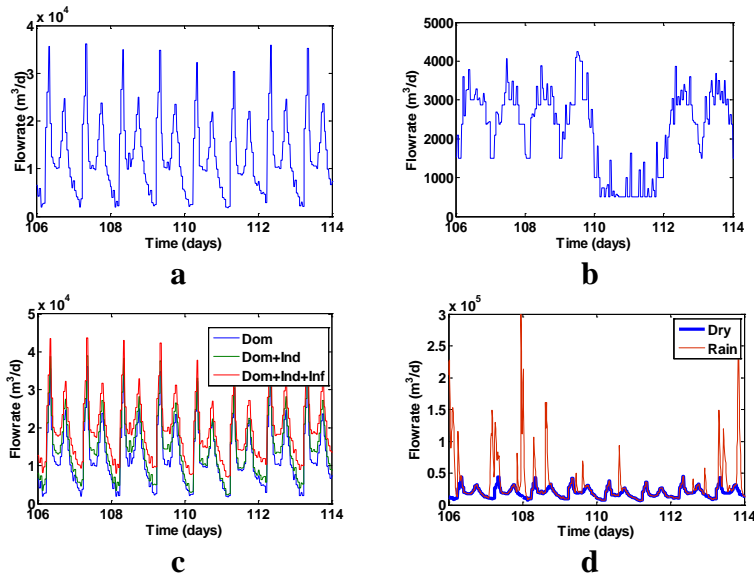

Figure 2: Dynamic profiles for household (a) and industry (b) flow rate generation. Different contributions to the dry weather WWTP inflow (c): domestic (Dom), industrial (Ind) and infiltration (Inf). Contribution of dry weather flow and rain to WWTP inflow (d).

Fig 3 describes oxygen (a&b) and ammonia (c&d) concentrations across the river stretch downstream of the WWTP effluent discharge point for two different rain events. Stretch 1 is immediately downstream of the effluent discharge whereas stretches 2 and 3 are further downstream the river. It can be seen that the lowest dissolved oxygen (DO) concentration is not always occurring at the point of discharge. For the first rain event (a), the DO minimum occurs close to the effluent discharge point whereas for the second rain event (b), the DO minimum occurs at a farther point. Factors affecting DO dynamics include WWTP effluent organic load, flow rate, time of the day etc. Ammonia dynamics are more straightforward, peak concentrations always occur at the discharge point and the concentration decreases downstream due to consumption by biomass. The dynamics of wastewater generation during dry/wet weather and their impact on WWTP/river performance can also be analysed by the model. Detailed results will be presented in the full paper.
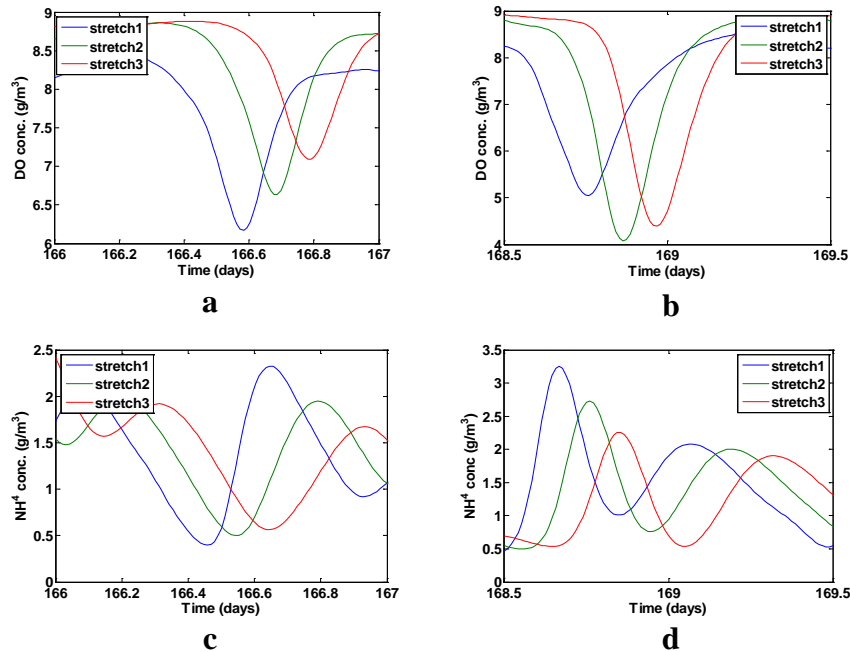
Figure 3: Influence of wet weather treatment plant discharges on river dynamics: (a&b) DO variation, (c&d) NH$_4$ dynamics.

4. Conclusions

An extension to the existing plant-wide BSM2 model is developed to include the catchment, sewer system and river. The dynamics and interactions between sewer system, WWTP and river are depicted and the possibility to evaluate the whole system using river quality based indicators is presented. The next step will be to provide a framework and case studies for evaluation of integrated control strategies using the system-wide model.

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