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A model library for simulation and benchmarking of integrated urban wastewater systems

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ABSTRACT

This paper presents a freely distributed, open-source toolbox to predict the behaviour of urban wastewater systems (UWS). The proposed library is used to develop a system-wide Benchmark Simulation Model (BSM-UWS) for evaluating (local/global) control strategies in urban wastewater systems (UWS). The set of models describe the dynamics of flow rates and major pollutants (COD, TSS, N and P) within the catchment (CT), sewer network (SN), wastewater treatment plant (WWTP) and river water system (RW) for a hypothetical, though realistic, UWS. Evaluation criteria are developed to allow for direct assessment of the river water quality instead of the traditional emission based metrics (for sewer overflows and WWTP discharge). Three case studies are included to illustrate the applicability of the proposed toolbox and also demonstrate the potential benefits of implementing integrated control in the BSM-UWS platform. Simulation results show that the integrated control strategy developed to maximize the utilization of the WWTP's capacity represents a balanced choice in comparison to other options. It also improves the river water quality criteria for unionized ammonia and dissolved oxygen by 62% and 6%, respectively.

Software availability

Name of the software:
BSM-UWS.
Developers:
R. Saagi, X. Flores-Alsina, S. Kroll, K.V. Gernaey, U. Jeppsson.
Programming language:
Matlab 13.0.
Software availability: The source code for the system-wide BSM can be obtained for free. Contact Dr Ulf Jeppsson, division of Industrial Electrical Engineering and Automation (IEA), Lund University, Box 118, SE-221 00 Lund, Sweden (ulf.jeppsson@iea.lth.se). The software is documented and interested readers will be able to reproduce the results summarized in this article, and then modify the software for their own purposes as well.

1. Introduction

The main objective of integrated modelling is to link various sections of the urban wastewater system (UWS) (catchment (CT), sewer network (SN), wastewater treatment plant (WWTP) and receiving water system (RW)) together to provide a unified platform for design and analysis of wastewater infrastructures in urban areas (Benedetti et al., 2013). Such a tool enables direct evaluation of UWS dynamic performance (or of individual sections) based on river water quality instead of relying on traditional emission based evaluation. Significant progress has been made in the field of integrated modelling ever since it was first proposed by Beck (1976) (e.g. Fronteau et al., 1997; Rauch et al., 2002; Muschalla et al., 2009; Benedetti et al., 2013; Bach et al., 2014). It is now well established that optimization of sub-system performance (SN or WWTP) does not necessarily lead to improvements in river quality (Rauch and Harremoës, 1999) and a more holistic approach is required (Lijklema et al., 1993). Although research has highlighted the need of integrated modelling for a long time, a strong incentive for receiving water quality based evaluation of UWS performance has been provided by the EU Water Framework Directive, which calls

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Nomenclature

$(P)_{\text{eff,WWTP}}$	Pollutant (P) total load at WWTP effluent (kg) (P =BOD$_5$, COD, TSS, TKN, P$_{\text{org}}$ and P$_{\text{inorg}}$)
$(P)_{\text{EMC}}$	Pollutant (P) EMC (g/m^3)
$(P)_{\text{in,WWTP}}$	Pollutant (P) total load at WWTP inlet (kg)
$(P)_{\text{ovf}}$	Pollutant (P) total load in overflow (kg)
AER1	Aerobic reactor 1
AER2	Aerobic reactor 2
AER3	Aerobic reactor 3
ANAER1	Anaerobic reactor 1
ANAER2	Anaerobic reactor 2
ANOX1	Anoxic reactor 1
ANOX2	Anoxic reactor 2
BOD$_5$	5-day biological oxygen demand
BP$_1$	Bypass 1 (before primary clarifier)
BP$_2$	Bypass 2 (after primary clarifier)
$C_{\text{max,NH3}}$	Hourly maximum concentration for unionized ammonia (g N/m^3)
$C_{\text{min,DO}}$	Hourly minimum concentration for dissolved oxygen (g/m^3)
COD	Chemical oxygen demand
COD$_{\text{part}}$	Particulate COD
COD$_{\text{sol}}$	Soluble COD
DO	Dissolved oxygen
EMC	Event mean concentration (g/m^3)
EQI	Effluent quality index (kg pollution units/d)
h_{STi}	Height of storage tank i
IQI	Influent quality index (kg pollution units/d)
$K_{\text{L}}a_{\text{AER(i)}}$	Oxygen transfer coefficient for aerobic reactor i (d^{-1})
MLSS	Mixed liquor suspended solids
NH$_3$	Unionized ammonia
NH$_4^+$	Ammonia
NO$_3^-$	Nitrate
N_{ovf}	Yearly overflow frequency (events/year)
OVF$_{\text{(i)}}$	Overflow at location no. i
OQI	Overflow quality index (kg pollution units/d)
PC	Primary clarifier
P$_{\text{inorg}}$	Inorganic phosphorus
PO$_4^3$	Phosphate
P$_{\text{org}}$	Organic phosphorus
Q_{intr}	Internal recirculation rate (m^3/d)
$Q_{\text{in,WWTP}}$	Inflow to WWTP (m^3/d)
$Q_{\text{max,BP1}}$	Maximum flow at bypass 1 (m^3/d)
$Q_{\text{max,BP2}}$	Maximum flow at bypass 2 (m^3/d)
$Q_{\text{max,ST2}}$	Maximum throttle flow for ST$_2$ (m^3/d)
$Q_{\text{max,ST5}}$	Maximum throttle flow for ST$_5$ (m^3/d)
$Q_{\text{max,ST6}}$	Maximum throttle flow for ST$_6$ (m^3/d)
$Q_{\text{pump,ST1}}$	Pumping rate at ST$_1$ (m^3/d)
$Q_{\text{pump,ST4}}$	Pumping rate at ST$_4$ (m^3/d)
Q_{r}	Sludge recycle rate (m^3/d)
$Q_{\text{throttle,ST4}}$	Maximum throttle flow for off-line tank ST$_4$ (m^3/d)
Q_{w}	Sludge wastage rate (m^3/d)
RST	Rainwater storage tank
RW$_{\text{(i)}}$	River water stretch i
SC$_{\text{(i)}}$	Sub-catchment i
Sec.C	Secondary clarifier
$S_{\text{NH4,RW16}}$	Sensor measurement for ammonia (NH$_4^+$) at river stretch 16 (g N/m^3)
$S_{\text{O2,AER2}}$	Sensor measurement for oxygen concentration at aerobic reactor 2 (AER2) (g/m^3)
ST$_{\text{(i)}}$	Storage tank i
$S_{\text{TSS,eff}}$	Sensor measurement for total suspended solids (TSS) at WWTP effluent (g N/m^3)
$T_{\text{exc,DO}}$	Yearly exceedance duration for dissolved oxygen in river (h)
$T_{\text{exc,NH3}}$	Yearly exceedance duration for unionized ammonia in river (h)
TKN	Total Kjeldahl nitrogen
T_{ovf}	Yearly overflow duration (days/year)
TSS	Total suspended solids
V_{ovf}	Yearly overflow volume (m^3)
WWTP$_{\text{eff}}$	Wastewater treatment plant effluent discharge into the river system

for achieving “good ecological and chemical status in all rivers” (EU, 2000). Today, tools for integrating sub-system models running on different platforms exist (Gregersen et al., 2007) and case studies illustrating their usage are available in the literature (Reußner et al., 2008; Van Assel et al., 2010). Commonly used commercial simulation software packages (e.g. SIMBA (ifak, Germany), WEST (DHI, Denmark)) provide libraries that allow users to develop system-wide models on a single platform. Additionally, several modelling libraries are developed by various researchers (e.g. Schütze, 1998; Achleitner et al., 2007; Mannina, 2005; Freni et al., 2010b; Willems and Berlamont, 2002).

Design and evaluation of (local/global) control strategies are two of the major areas where integrated models showed their full potential (e.g. Schütze et al., 2002; Meirlaen et al., 2002; Langeveld et al., 2013; Seggelke et al., 2005). Some of the studies were extremely successful, provided a lot of scientific inspiration for further control development and clearly demonstrated the benefits of using integrated approaches. Nevertheless, the evaluation/comparison of these control strategies, either real or model-based, is difficult. This is due to a number of reasons, including: i) variation in the characteristics of the UWS (catchment layout, sewer and WWTP design, river water quality etc.); ii) differences in the underlying models for describing the hydraulic, biological and physico-chemical processes in the UWS; and iii) the lack of a common evaluation method to compare the results. Hence, the objective comparison of the reported strategies has been a challenge.

A similar problem in the WWTP modelling community is addressed by using Benchmark Simulations Models (BSMs). Several researchers working under the umbrella of the International Water Association (IWA) benchmarking task group developed different benchmarks (BSM1, BSM1_LT, BSM2) to facilitate an unbiased comparison of control strategies in WWTPs (Copp, 2002; Rosen et al., 2004; Nopens et al., 2010). These BSMs consist of pre-defined layouts, process models, sensor/actuator models, influent characteristics and evaluation criteria (Gernaey et al., 2014). They have seen huge success (500 + publications) and are widely accepted in the research/practice community (Jeppsson et al., 2013). Similar efforts in the urban drainage community have been made where pre-defined sewer system layouts are used for comparing various real time control strategies and static design options (Borsányi et al., 2008; Schütze et al., 2015). Besides the original objective of comparing control strategies (Stare et al., 2007; Flores-Alsina et al., 2008; Sweetapple et al., 2014), the different tools developed by the BSM group are also used to develop better solvers (Rosen et al., 2008; Flores-Alsina et al., 2015), model