Industrial Electrical Engineering and Automation

CODEN:LUTEDX/(TEIE-7275)/1-14/(2020)

# Benchmark Simulation Model for Integrated Urban Wastewater Systems

**Ramesh Saagi**

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University

# Benchmark Simulation Model for Integrated Urban Wastewater Systems

**Ramesh Saagi**

**IEA, Lund University, Sweden**

# Contents

# Preface

This short report summarizes the key findings and main conclusions of the PhD work by Dr Ramesh Saagi, IEA, Lund University, presented in June 2017. It does not provide any complete background and description of the methodology of the work, instead the interested reader can access the complete PhD thesis:

*"Benchmark Simulation Model for Integrated Urban Wastewater Systems – Model Development and Control Strategy Evaluation"*

via the web link https://www.iea.lth.se/publications/Theses/LTH-IEA-1083.pdf to discover all the details of the research.

# 1. Introduction

Various sections involved in the collection, transport, treatment and discharge of sewage and stormwater together comprise the urban wastewater system (UWS). In this chain of interlinked elements, the starting point for generation of wastewater/stormwater is the urban catchment. Sewage is generated from households and industries while stormwater is mainly the runoff from urban surfaces during rain events. The invisible underground sewer network transports the generated wastewater to the wastewater treatment plant (WWTP). As the name suggests, the WWTP is involved in removing the pollutants present in the raw sewage before discharging the treated effluent into receiving waters. Receiving waters form the final link in this chain (Figure 1). In many cases, this receiving water system is the starting point for the drinking water system for any downstream city (although this is outside the scope of this thesis). Historically, the objective of an UWS has been to convey the sewage away from the city in order to avoid health hazards to urban dwellers. However, owing to our increasing understanding of anthropological pressures on the natural ecosystem, the European Union has (re-)defined the objective of an UWS as to "protect the chemical and ecological status of a river" (Council of the European Communities, 2000).

In this context, it is essential to understand the interactions between different parts of an UWS in order to improve their performance individually as well as to protect the receiving waters in a holistic manner. Modelling can be a valuable tool not only for understanding the individual sections and their interactions but also for serving as an engineering tool to explore the potential for improvement in the performance using different approaches (e.g. process control, upgrading the existing infrastructure).

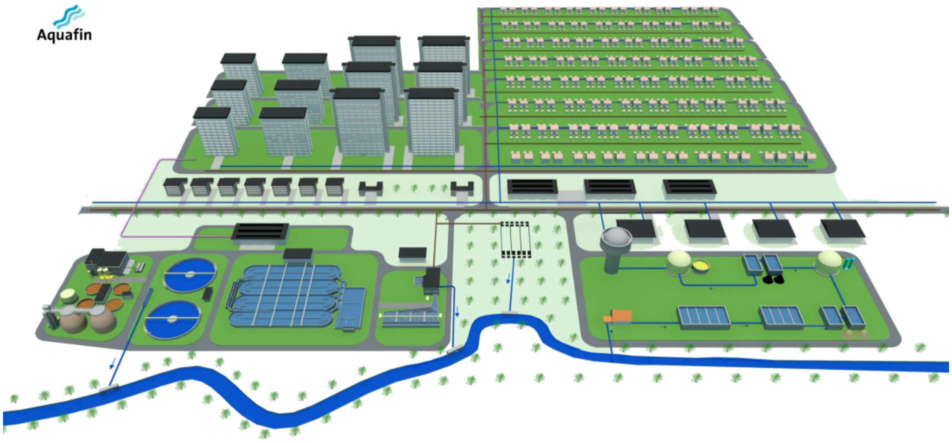

**Figure 1:** Various sections of an urban wastewater system which include: i) catchment (top); ii) sewer network (top and middle); iii) wastewater treatment plant (bottom left); and iv) receiving waters (bottom). (Copyright: Aquafin, Belgium. Reprinted with permission). Note that the drinking water system (bottom right) is outside the scope of this thesis.

## 2. Model Description

### *2.1. Catchment*

The most important state variables included in the catchment model are flow rate and five pollutant variables. COD is divided into soluble ($COD_{sol}$) and particulate ($COD_{part}$) fractions. Ammonium ($NH_4^+$), nitrate ($NO_3^-$) and phosphate ($PO_4^{3-}$) are modelled as soluble components. The model simulates the generation of wastewater from four major sources, namely: i) domestic (DOM); ii) industrial (IND); iii) stormwater (SW); and iv) infiltration to sewers (INF).

### *2.2. Sewer Network*

The generated wastewater and stormwater from the catchment model are conveyed to the WWTP through the sewer network. Also, excess flow beyond the sewer capacity is discharged into the river as sewer overflow. The model consists mainly of three elements, namely: i) TRANSPORT sub-model to describe the flow of wastewater/pollutants in the sewer; ii) STORAGE sub-model that represents various storage tank configurations and the control elements (CONTROL) present (e.g. pumps, throttle valves); and iii) FIRST-FLUSH sub-model that mimics the generation of high pollutant loads at the beginning of rain events.

### *2.3. Wastewater Treatment Plant*

The model library for WWTP unit operations that is developed for BSM1 and BSM2 (Gernaey et al., 2014) is re-used when developing the WWTP section for BSM-UWS. The major unit operations described are: i) primary clarifiers; ii) biological reactors; and iii) secondary clarifiers.

In the current version of the BSM-UWS, the sludge line is not considered. Hence, the model blocks for anaerobic digester and other sludge handling units are not described.

### *2.4. River Water System*

The complete river stretch is described by connecting a series of river system models, each describing the hydraulics and biochemical transformations taking place in that particular stretch. For the purpose of integrated modelling, the hydraulic processes are simplified and the biochemical transformations are described using a simplified version of River Water Quality Model 1 - RWQM1 (Reichert et al., 2001).

### *2.5. Interfaces*

As the state variables for the sewer network, WWTP and river models are different, model interfaces are required to transform the state variables from one model to another. Some of the state variables can be directly mapped while others are transformed. Three different interfaces are developed for the BSM-UWS model.

- SEWER-WWTP – Translates the pollutant state variables in the sewer (described as daily loads) to ASM2d state variables (described as concentrations). While some of the pollutants ($NH_4^+$, $PO_4^{3-}$) are directly mapped, others ($COD_{sol}$, $COD_{part}$) are fractionated into multiple ASM2d state variables.
- SEWER-RIVER – Converts the sewer state variables (load based) into RWQM1 state variables (concentration based). As in the case of the sewer-

WWTP interface, some of the pollutant state variables in the sewer are either directly mapped or fractionated into multiple RWQM1 state variables. Additionally, constant values are assumed for some state variables (e.g. inorganic carbon, algal biomass etc.) at the interface since these variables do not exist in the sewer model.

- WWTP-RIVER – Transforms the ASM2d state variables in the WWTP to RWQM1 state variables in the river. While some of the state variables can be directly mapped, state variables that are present only in the ASM2d model are first transformed to other variables that are present in both the models. It is assumed that the state variables undergo biological processes described in the ASM2d model instantaneously. Once transformed, they can be mapped directly to RWQM1 state variables.

For all interfaces, mass balances for COD, carbon, nitrogen and phosphorus are maintained.

## 3. Evaluation Criteria

### *3.1. Sewer Network*

Sewer network performance during rain events is generally assessed by the flow rate and pollutant loads that are discharged into the river system (the lower, the better). The major evaluation criteria are mentioned below.

1. Overflow duration ($T_{\mathrm{ovf}}$, d.yr$^{-1}$): The total overflow duration for a given year /evaluation period.
2. Overflow frequency ($N_{\mathrm{ovf}}$, events.yr$^{-1}$): Represents the number of overflow events annually. Two overflow events are separated if there is at least one hour difference in time between these events.
3. Overflow volume ($V_{\mathrm{ovf}}$, m$^3$.yr$^{-1}$): The total volume of overflow from all overflow locations that reaches the receiving water system in a year.
4. Overflow quality index (*OQI*, kg pollutant units.d$^{-1}$): An aggregated pollution index similar to the indices used in BSM WWTP models. It considers the pollutant load from different pollutants (COD, BOD, TSS, TKN, $NO_3^-$ and $PO_4^{3-}$) and assigns weights to each one of them. The *OQI* is the sum of the total load for each pollutant multiplied by its individual weight. The weights for individual pollutants are similar to those used in the BSM2 and BSM1 models.
5. Hourly maximum concentration ($C_{\mathrm{max}}$, g.m$^{-3}$): The concentration that is continuously exceeded for a period of at least 1 hour. $C_{\mathrm{max}}$ is calculated for TSS, TKN and $PO_4^{3-}$.
6. Exceedance duration ($T_{\mathrm{exc}}$, d.yr$^{-1}$): The total duration for which the pollutant concentration exceeds a pre-defined threshold limit. It represents the duration of acute pollutant discharge to the receiving water system. Pollutants considered are TSS, TKN and $PO_4^{3-}$.

All the above criteria are described for the entire sewer network but can also be computed for each overflow location individually.

### *3.2. Wastewater Treatment Plant*

The evaluation criteria that have been developed for the BSM1 and BSM2 models can be calculated in the BSM-UWS as well. The major criteria are described here.

1. Influent Quality Index (*IQI*) (kg pollutant units.$d^{-1}$): An aggregated index that computes the cumulative pollutant load in the influent wastewater for six major pollutants (COD, BOD, TSS, TKN, $NO_3^-$, $PO_4^{3-}$). Each pollutant has a weight factor assigned to it.
2. Effluent Quality Index (*EQI*) (kg pollutant units.$d^{-1}$): An aggregated index computed for the wastewater effluent in a similar manner as the *IQI*. *EQI* includes both the bypass and the overflow from the secondary settler.
3. Operational Cost Index (*OCI*): It considers the operational costs from aeration, pumping, mixing, sludge handling and external carbon addition. Similar to the quality criteria, weights are assigned to each of the contributing operations and a net cost index is computed.

### *3.3. River Water System*

Four evaluation criteria are described to assess the chemical quality of the river, mainly in terms of un-ionized ammonia ($NH_3$) and dissolved oxygen (DO). The criteria are calculated as a cumulative index for the entire river.

1. Exceedance duration ($T_{exc}$, d.$yr^{-1}$): $T_{exc,DO}$ and $T_{exc,NH3}$ represent the total duration in a year for which the respective concentrations exceed a threshold value. The threshold values used are: $NH_3$ – 0.018 g N.$m^{-3}$ and DO – 6 g.$m^{-3}$. The values are based on the limits prescribed for salmonid species in the Urban Pollution Management (UPM) manual (FWR, 2012).
2. Hourly minimum oxygen concentration ($C_{min,DO}$, g.$m^{-3}$): Minimum dissolved oxygen concentration that is continuously reached for a duration of at least one hour.
3. Hourly maximum ammonia concentration ($C_{max,NH3}$, g N.$m^{-3}$): Un-ionized ammonia concentration that is continuously exceeded for a period of at least one hour.

## 4. Layout and Characteristics

The system layout consists of an urban catchment (with different sub-catchments) that generates sewage during dry weather and additionally stormwater during rain events (Figure 2). The sewer network connects all sub-catchments to the WWTP and transports all the collected wastewater to the treatment facility. During rain events, any excess flow beyond the capacity of the sewer network overflows into the river system.

**Table 1**: System characteristics (catchment and sewer network) for the BSM-UWS.

| Sub-catchment | Area (ha) | PE | DWF ($m^3$.$d^{-1}$) | | Storage ($m^3$) |
|---|---|---|---|---|---|
| | | | DOM | IND | |
| **1** | 99 | 15 920 | 2 390 | | 5 000 |
| **2** | 21 | 3 920 | 590 | 2 500 | 1 000 |
| **3** | 29 | 2 960 | 440 | | |
| **4** | 71 | 9 600 | 1 440 | | 4 400 |
| **5** | 71 | 7 840 | 1 180 | | 3 600 |
| **6** | 249 | 39 760 | 5 960 | | 8 100 |
| **Total** | **540** | **80 000** | **12 000** | **2 500** | **22 100** |

DWF: Dry weather flow; DOM: Domestic; IND: Industrial

### 4.1. Catchment

The hypothetical urban catchment structure is adopted from the ATV A 128 case study (ATV, 1992). It consists of six sub-catchments ($SC_1 \ldots SC_6$) connected to the WWTP through a sewer network (Figure 2). The catchment has a total area of 540 hectares with 80 000 population equivalents. During dry weather, daily average wastewater generation is 19 000 $m^3.d^{-1}$. Contribution from domestic sources is 12 000 $m^3.d^{-1}$ and industrial sources is 2 500 $m^3.d^{-1}$. Daily average infiltration to sewers is assumed to be 4 500 $m^3.d^{-1}$. $SC_2$ has both an industrial and domestic section, while the remaining sub-catchments generate domestic wastewater only (Table 1).

### 4.2. Sewer Network

The sewer network consists predominantly of combined sewer networks. Five of the six sub-catchments ($SC_1$, $SC_2$, $SC_3$, $SC_4$ and $SC_6$) are connected to combined sewer networks whereas only $SC_5$ is connected to a separate sewer network (see Figure 2). The sewer network at each sub-catchment includes a storage tank (except at $SC_3$). Two different storage tank configurations are used. Online pass-through tanks are used at four locations ($ST_1$, $ST_2$, $ST_5$ and $ST_6$) whereas $ST_4$ is an offline bypass tank. The outflows from online tanks are regulated by throttle valves/pumps, whereas those from offline tank are regulated by pumps with fixed pumping capacity. The total available storage volume is 22 100 $m^3$ (approx. 40 $m^3.ha^{-1}$ of catchment area). Individual storage volume for each tank (connected to a sub-catchment) is detailed in Table 1. The sewer overflows are discharged at five locations to the river system.

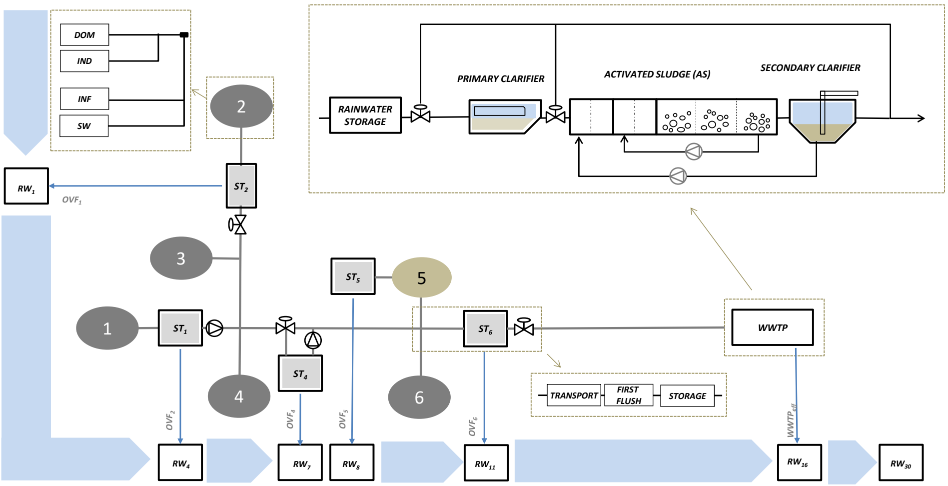

**Figure 2**: BSM-UWS layout – sub-catchments ($SC_1$, $SC_2$, $SC_3$, $SC_4$, $SC_5$ and $SC_6$), sewer network with storage tanks ($ST_1$,$ST_2$, $ST_4$, $ST_5$ and $ST_6$), WWTP and river water system.

### 4.3. Wastewater Treatment Plant

An extended BSM1-ASM2d plant layout is used for the WWTP (Flores-Alsina et al., 2012a). The biological section includes two anaerobic tanks (ANAER1, ANAER2) (2 x 1 000 $m^3$), two anoxic tanks (ANOX1, ANOX2) (2 x 1 500 $m^3$) and three aerobic tanks (AER1, AER2, AER3) (3 x 3 000 $m^3$). A primary clarifier (PC) (900 $m^3$) and a secondary clarifier (Sec.C) (area – 2 500 $m^2$) are used for separation processes before and after the biological reactors, respectively. In addition, a rainwater storage tank (RST) (8 000 $m^3$) at the beginning of the WWTP and two bypass facilities ($BP_1$, $BP_2$) (before and after the primary clarifier) are included. $BP_1$ has a threshold of 90 000

$m^3.d^{-1}$ (any flow in excess of the threshold is bypassed and reaches the river system) while $BP_2$ has a threshold of 70 000 $m^3.d^{-1}$.

### *4.4. River Water System*

A 30 km long urban river stretch is represented by a series of river model blocks (where each block contains the hydraulic and biochemical process model for a 1 km stretch of the river). It is assumed that the river has a uniform bottom width of 7 m and is trapezoidal in shape. From Figure 2, it can be seen that the river segment is modelled even after the WWTP discharge location. This is essential as the worst river quality does not necessarily occur at the point of effluent discharge. The river has a mean annual base flow rate of 72 500 $m^3.d^{-1}$. Additional runoff from an upstream catchment (area – 500 ha) reaches the river during rain events. The upstream pollutant concentrations are assumed to be constant and identical for both wet and dry weather conditions. WWTP effluent ($WWTP_{eff}$-$RW_{16}$) as well as sewer overflows from five overflow locations ($OVF_1$-$RW_1$, $OVF_2$-$RW_4$, $OVF_4$-$RW_7$, $OVF_5$-$RW_8$ and $OVF_6$-$RW_{11}$) reach the river system.

## 5. BSM-UWS – Control Strategies

Three control strategies are devised and evaluated using the BSM-UWS. The case studies are developed to demonstrate the ability of the tool when modelling and evaluating local as well as integrated control alternatives. The focus has primarily been on developing simple yet realistic control strategies and not on identifying the best/optimum solution for the system. Open loop (OL) represents the default set up without any active control strategy. The three case studies evaluated are:

i. control of dissolved oxygen concentration in the WWTP aeration tanks (C3);
ii. modifying the biological capacity at the WWTP (by changing the bypass limits) based on river water quality (C4);
iii. optimize storage tank utilization based on influent flow rate to the WWTP (C5).

**Table 2**: Performance of various sections under OL, C3, C4 and C5.

| | **OL** | **C3** | **C4** | **C5** |
|---|---|---|---|---|
| **Sewer** | | | | |
| **$V_{ovf}$ ($m^3.yr^{-1}$)** | 203 400 | 203 400 | 203 400 | 207 700 |
| ***OQI* (kg poll. units.$d^{-1}$)** | 940 | 940 | 940 | 957 |
| **WWTP** | | | | |
| ***IQI* (kg poll. units.$d^{-1}$)** | 92 714 | 92 714 | 92 714 | 94 377 |
| ***EQI* (kg poll. units.$d^{-1}$)** | 6 778 | 6 466 | 6 409 | 6 505 |
| **River** | | | | |
| **$T_{exc,NH3}$ ($d.yr^{-1}$)** | 16.2 | 5.5 | 6.2 | 7.8 |
| **$T_{exc,DO}$ ($d.yr^{-1}$)** | 12.8 | 13.7 | 12.1 | 11.4 |

### *5.1. Control of Dissolved Oxygen Concentration in the WWTP Aeration Tanks (C3)*

The dissolved oxygen concentrations in the three aeration tanks (AER1, AER2 and AER3) are controlled using a feedback controller. The oxygen level in AER2 is compared to an oxygen set point of 2 $g.m^{-3}$ and the error is used to regulate the oxygen supply in AER2 using a Proportional-Integral (PI) controller. For tanks AER1 and AER3, a less precise approach is chosen. The oxygen supply rate for AER2 is adjusted using correction factors in order to regulate the oxygen supply to these tanks. Although, this does not lead to precise control of oxygen concentrations in AER1 and AER3, it is considered as a practical simplification in order to avoid using a large number of control loops.

From the WWTP perspective, C3 is successful in: i) maintaining the desired DO concentration set point in AER2 and also loosely regulating the oxygen supply in AER1 and AER3; and ii) improving the effluent quality (*EQI* decreases by 5 % in comparison to OL) due to improved nitrification (Figure 3). However, it does not lead to improvements in all the river criteria. While $T_{\mathrm{exc,NH3}}$ reduces significantly (66 % lower than OL), $T_{\mathrm{exc,DO}}$ increases by 7 % (Table 2). The drop in $T_{\mathrm{exc,NH3}}$ is mainly due to the lower $NH_4^+$ concentration in the WWTP effluent. The reason for the increase in $T_{\mathrm{exc,DO}}$ is not straightforward. It is observed that the DO control leads to marginally higher mixed liquor suspended solids concentration in the activated sludge reactors (better biomass growth with improved oxygen supply). During rain events, this causes higher TSS washoff concentration in the settler overflow leading to lower DO concentrations in the river.

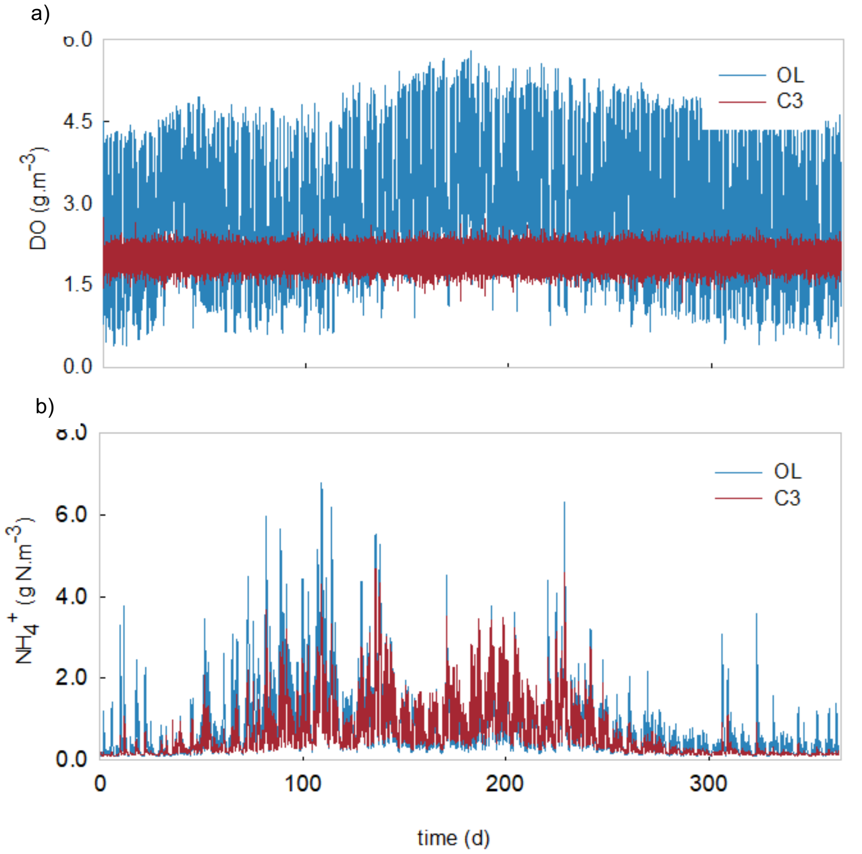

**Figure 3**: Variation in DO concentration in AER2 (a) and $NH_4^+$ concentration in the WWTP effluent due to the effect of DO controller (C3) (b). Day 0 is 1st July.

### 5.2. *Modifying the Biological Capacity of the WWTP Based on River Water Quality (C4)*

The integrated control strategy (C4) regulates the bypass limits at the WWTP (thereby controlling the maximum treatment capacity of the WWTP) based on the river water quality (in terms of $NH_4^+$ concentration) at the point of WWTP effluent discharge. If the $NH_4^+$ concentration in the river exceeds 0.4 g N.m$^{-3}$, indicating that there is a high load of untreated wastewater reaching the river system, the maximum capacity of the WWTP is increased by 20 % (by rising the bypass limits). However, in order to ensure that this will not lead to loss of biomass (and reduced nitrification capacity), the control strategy is switched off when the effluent suspended solids concentration is higher than 60 $g.m^{-3}$. Also, the oxygen control at the WWTP (C3) is active.

The objective of utilizing the WWTP biological treatment capacity to the maximum extent possible is achieved by the control strategy. Figure 4a shows the reduction in bypass volumes. The strategy leads to a 45 % drop in bypass volume when compared to OL. The reduced overflow volume leads to a lower *EQI* (which means better effluent quality) in spite of sending more wastewater to treatment (3 % and 1 % lower than OL and C3, respectively).

The improvement in river quality in comparison to OL is clearly evident in both criteria. Figure 4b shows lower river ammonium concentration due to C4. $T_{\text{exc,NH3}}$ decreases by 62 % and $T_{\text{exc,DO}}$ decreases by 6 %. However, when compared to river water quality in C3, the results are mixed. While $T_{\text{exc,NH3}}$ increased by 10 %, $T_{\text{exc,DO}}$ decreased by 12 % (Table 2). The increase in $T_{\text{exc,NH3}}$ is due to increased $NH_4^+$ concentration in the effluent in spite of lower *EQI*. $T_{\text{exc,DO}}$ has reduced due to a lower bypass volume and hence less organic load to the river.

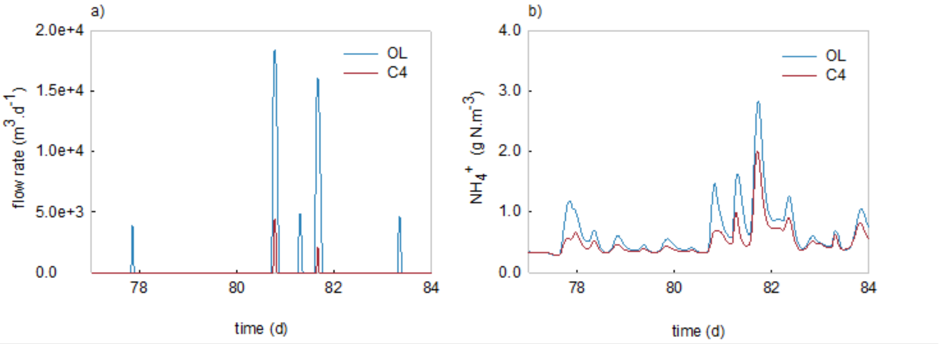

**Figure 4**: Effect of C4 on bypass flow rate (a) and $NH_4^+$ concentration in the river stretch where WWTP effluent is discharged (b). Day 77 is 16th September.

### 5.3. *Optimize Storage Tank Utilization Based on Influent Flow Rate to WWTP (C5)*

Taking inspiration from the control strategies implemented in Weyand (2002) and Kroll et al. (2016), a rule-based integrated control strategy that manipulates the behaviour of the storage tanks based on flow rate information at the inlet to the WWTP is implemented. If the inflow ($Q_{\text{in,WWTP}}$) to the WWTP is higher than 80 000 $m^3.d^{-1}$ and there is capacity available in the storage tank ($h_{\text{ST}} < 4$ m): i) only one pump is used in the pumping station at $ST_1$ (i.e., the pumping capacity ($Q_{\text{pump,ST1}}$) is reduced to 63 % of the maximum capacity); ii) at $ST_2$ and $ST_6$, the valve openings ($Q_{\text{max,ST2}}$, $Q_{\text{max,ST6}}$) are reduced by 50 % and 30 %, respectively; and iii) at $ST_4$, the throttle flow ($Q_{\text{throttle,ST4}}$) is reduced by 50 %. C3 (WWTP DO control) is also active in C5.

The control strategy shows better utilization of the storage tanks. Figure 5a shows that $ST_6$ stores water for a longer duration in C5 than in the OL case. Also, the maximum throttle flow from $ST_4$ is reduced in C5 (Figure 5b). This means that more flow is directed to $ST_4$ instead of being sent downstream. This increases $V_{\text{ovf}}$ and *OQI* marginally (1 % increase compared to OL). As the control strategy tries to store more water, there are situations where it leads to increased overflows from the storage tanks.

With better utilization of the storage tanks to reduce the peak flows, the inflow to the WWTP shows reduced peaks (Figure 5c). Surprisingly, this does not translate to improved influent quality. With the storage tanks storing more wastewater, an increased amount of pollution is sent to the WWTP leading to higher *IQI* (2 % higher than OL). However, the *EQI* decreases by 4 % compared to OL due to reduced peak flows.

The changes in the performance of the WWTP strongly affect the river water quality.

Table 2 indicates that, while $T_{\mathrm{exc,NH3}}$ is better (51 % lower) than the OL case, it is 41 % higher than that in C3. As the effluent $NH_4^+$ concentration from the WWTP increases (reflected in the higher *EQI* values compared to C3), $T_{\mathrm{exc,NH3}}$ in the river also increases. However, due to reduced peak flows resulting in lower bypass volumes from the WWTP, $T_{\mathrm{exc,DO}}$ improves by 11 % and 17 % in comparison to OL and C3. The reduced bypass flows lead to a drop in the organic load to the river thereby improving the oxygen levels in the river (Figure 5d).

In conclusion, a clear winner in terms of the evaluation criteria is not directly evident. The choice of control strategy depends on the needs of the actual UWS. In order to reduce the high un-ionized ammonia concentrations in the river, C3 is the choice (from the evaluated options) while C5 leads to improved oxygen concentrations and C4 can be considered as a good compromise considering both the criteria. Hence, a multi-criteria approach is needed in order to arrive at the final choice of control strategy from the evaluated case studies.

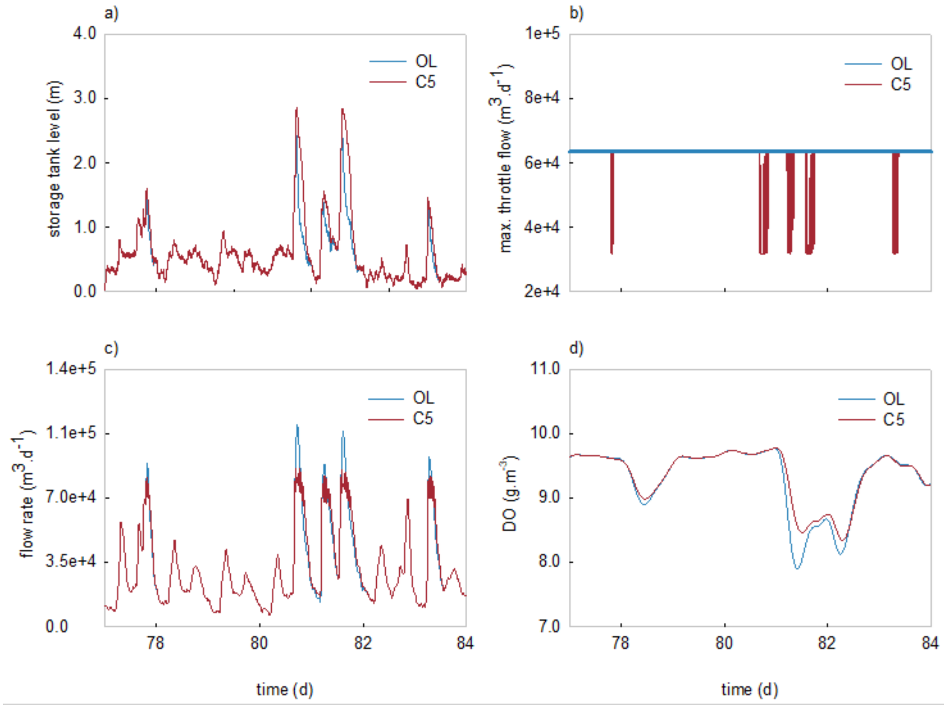

**Figure 5**: Effect of C5 on $ST_6$ level (a), $ST_4$ maximum throttle flow (b), WWTP influent flow rate (c) and DO concentration in the river (d) in comparison to OL. Day 77 is 16th September.

# 6. Summary

## 6.1. *Key Contributions*

The major contributions from the research are summarized below together with an overview of the papers published/written during the research period.

- An open-source, freely distributed integrated Benchmark Simulation Model (BSM-UWS) is developed, which includes description of flow rate and pollutant transformations in: i) catchments; ii) sewer networks; iii) wastewater treatment plants; and iv) river water systems. The models library can be used as a benchmarking tool as well as for developing integrated models for other real cases. The individual model blocks (e.g. storage tanks, river models etc.) can also be used as standalone models to simulate limited sections of the UWS.
- Evaluation criteria using traditional metrics for WWTP effluent and sewer overflows are defined. More importantly, holistic evaluation criteria based on the chemical quality of river water systems are developed.
- Various case studies highlighting control strategies (local/integrated) as well as structural modifications that can be evaluated using the BSM-UWS are presented and evaluated. This demonstrates the usefulness and applicability of BSM-UWS and integrated modelling studies.

## 6.2. *Potential Applications of BSM-UWS*

The major areas where the BSM-UWS can potentially be used are mentioned below.

- Benchmarking control strategies – This is the primary objective behind the development of BSM models and it is expected that BSM-UWS will be used in a manner similar to BSM1 and BSM2 for this purpose. In particular, various rule-based control strategies (e.g. Seggelke et al., 2005; Vanrolleghem et al., 2005), optimization routines (e.g. Fu et al., 2008; Muschalla, 2008) and permitting frameworks (e.g. Meng et al., 2016) can be evaluated using this layout.
- Adapting the model to other catchments – With the model library available (and distributed freely) for the BSM-UWS, system-wide models for real catchments can be developed and evaluated using the BSM model library as a software tool. Additionally, the toolbox can be used to model the individual sections (or select components) only.
- Including new model features – The standard layout and model library (with access to verified source code) makes the BSM family of models an ideal choice to implement new model features and evaluate them. Various model additions, such as biological reactions in the sewer network (Huisman & Gujer, 2002) and sediment dynamics in the river (Reichert et al., 2001) can be implemented within the BSM-UWS layout.

### *6.3. Commercial Software for Integrated Modelling*

The WEST modelling software offers WESTforIUWS which can simulate the catchment, sewer, WWTP and river water system of an integrated UWS. It offers possibilities to evaluate water quality based objectives for both long term and short term evaluation periods. Additionally, uncertainty and sensitivity analysis of the models can also be performed.

SIMBA# water is developed by Institut für Automation und Kommunikation (ifak), Germany, and is used for simulation of the integrated UWS. The software consists of a model library to simulate processes in sewers, WWTPs and rivers. Simplified hydrological models as well as hydrodynamic models are available for the sewer network. Various modules for biochemical and physical processes in the WWTP and also different possibilities to simulate biochemical processes in the river are included. Additionally, it facilitates easy implementation of control studies. There is a possibility to program the controllers using industry standard languages, such as structured text, petri nets etc.

### *6.4. Model Limitations*

Simplifications are made in describing the different sections (e.g. hydrological processes in the catchment, flow phenomena in the sewer network, biological processes in WWTP and river system) considering the purpose of the study. Although the BSM-UWS layout can be used to evaluate various control strategies, the best control strategy thus obtained may not necessarily perform in a similar manner for another catchment due to differences in the layout and design capacities. However, the control principles demonstrated for the BSM-UWS can be transferable to other catchments. The model library mostly uses standard approaches that are well established. However, they are currently only used to describe a hypothetical UWS and not fully calibrated for a real case study.

## References

Council of the European Communities (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy. *Official Journal of the European Communities, L 327*, 1-72.

Reichert, P., Borchardt, D., Henze, M., Rauch, W., Shanahan, P., Somlyódy, L. and Vanrolleghem, P.A. (2001). *River Water Quality Model No. 1*. Scientific and Technical Report Series, IWA Publishing, London, UK.

Seggelke, K., Rosenwinkel, K.H., Vanrolleghem, P.A. and Krebs, P. (2005). Integrated operation of sewer system and WWTP by simulation-based control of the WWTP inflow. *Water Science and Technology, 52*(5), 195-203.

Vanrolleghem, P.A., Benedetti, L. and Meirlaen, J. (2005). Modelling and real-time control of the integrated urban wastewater system. *Environmental Modelling & Software, 20*(4), 427-442.

Fu, G., Butler, D. and Khu, S.-T. (2008). Multiple objective optimal control of integrated urban wastewater systems. *Environmental Modelling & Software, 23*(2), 225-234.

Muschalla, D. (2008). Optimization of integrated urban wastewater systems using multi-objective evolution strategies. *Urban Water Journal, 5*(1), 59-67.

Meng, F., Fu, G. and Butler, D. (2016). Water quality permitting: From end-of-pipe to operational strategies. *Water Research, 101*, 114-126.

Huisman, J.L. and Gujer, W. (2002). Modelling wastewater transformation in sewers based on ASM3. *Water Science and Technology, 45*(6), 51-60.

Reichert, P., Borchardt, D., Henze, M., Rauch, W., Shanahan, P., Somlyódy, L. and Vanrolleghem, P.A. (2001a). *River Water Quality Model No. 1*. Scientific and Technical Report Series, IWA Publishing, London, UK.

FWR (2012). *Urban pollution management manual*. 3rd Edition, Foundation for Water Research, Marlow, UK.