Conceptual Quality Modelling and Integrated Control of Combined Urban Drainage System

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Abstract: This paper presents the first results of conceptual quality modelling approach oriented to the integrated real-time control (RTC) strategy for urban drainage networks (UDN) and wastewater treatment plants (WWTP) developed in the European project LIFE EFFIDRAIN (Efficient Integrated Real-time Control in Urban Drainage and Wastewater Treatment Plants for Environmental Protection). Model predictive control (MPC) has been selected as a proper RTC to minimize the polluting discharge in case of raining events. The simulator SWMM5 was modified to integrate a lumped conceptual model for total suspended solids (TSS) called SWMM-TSS, which has been used as virtual reality for calibration and validation of the proposed modelling approaches in Perinot network, a real case study in Bordeaux.

Keywords: simplified quality modelling, suspended solid, model predictive control, SWMM

INTRODUCTION

Integrated urban wastewater systems (IUWS) which consider urban drainage networks (UDN), wastewater treatment plants (WWTP) and the receiving body are designed to collect and convey urban wastewater and storm water run-off through sewer network to WWTP for treatment before released to the environment. During heavy rain events, mixed sewage of rain and urban wastewater can overload the system and produce combined sewer overflows (CSO), which are harmful to the environment (Ahyerre et al., 1998; Becouze et al., 2009; Gasperi et al., 2008; Gromaire et al., 2001; Joseph et al., 2014a; Krejci et al., 2005). Up to now, sewer network and WWTPs used to be operated separately. In order to optimize efficiency of IUWS and minimize impact on the receiving environment, integrated and coordinated control of the infrastructures of IUWS using the real-time hydraulic and quality data is proposed as the main goal of the EFFIDRAIN project (www.life-effidrain.eu).

Current available results (Beck, 1976; Bulter and Schutze, 2005; Beeneken et al. 2013; Cembrano et al., 2004; Fu et al., 2007; Fu et al., 2008; Fu et al., 2010; Glasgow et al., 2004; Joseph et al., 2014b; Schilling, 1989; Schutze et al. 2002; Schutze et al., 2003; Xu et al. 2013;) have proved that real-time control (RTC) is a reliable solution to achieve better performance in the operation of IUWS. Among the RTC methods, model predictive control (MPC), which can optimize control not only with the current measurements but also predictive behaviors in a certain horizon, has been successfully implemented into flow models of advanced urban drainage networks (Cembrano et al., 2004; Pleau et al., 2005; Puig et al., 2009; Vanrolleghem et al., 2005).

Considering the complexity of the hydraulics and the quality spatial/temporal evolution in IUWS, appropriate conceptual quality models are required to apply RTC efficiently in IUWS taking into account effluent quality. These models should allow the RTC to compute estimations of the quality evolution in the UDN during a storm event (Ahyerre et al., 1998). Because of the input data uncertainty and calibration difficulty, modelling the generation and transportation of pollution in IUWS during a storm event is complex. In (van Rijn, 1984; Rouse, 1937; Macke, 1980; Ackers and White, 1973), some physically-based models which can present quality dynamics in IUWS are proposed, but the mathematical equations are mainly due to high computational time requirement.

The main contribution of this paper is proposing a control-oriented conceptual quality modelling approach to represent dynamics of total suspended solid (TSS) in both sewer network and WWTPs, which will be combined with the hydraulic model (Joseph et al., 2015) of IUWS used for MPC control. A detailed TSS model, developed using SWMM-TSS (Rossman, 2015) is used as a virtual reality to calibrate and validate the proposed simplified TSS models. The Perinot network, which is a real sewer network in Bordeaux, has been selected as case study. Analysis of the calibration and validation results and conclusions of the simplified modelling approaches are also presented. State space equations of the control-oriented model and implementations of MPC are discussed for the future use of the proposed quality models in integrated RTC.

SIMPLIFIED MODELLING APPROACHES

In order to apply RTC to IUWS, simplified modelling structures are necessary (Cluckie, 1999; Norreys and Cluckie, 1997; Puig et al., 2009). TSS has been selected as a representative variable of water quality, because it can be correlated to turbidity, which may be measured on line at different points in the network. Additionally, TSS may also be used as a good indicator of pollution.

Physically, TSS models are affected by solid sediment accumulation over urban catchments; solid sediment washoff by rainfall; transport, erosion and deposition of solids in sewer networks and detention tanks (Bertrand-Krajewski, 2006; Rossman, 2015).

The proposed conceptual modelling approaches are designed to predict the evolution of TSS over the predictive control horizon.

The simplified dynamic behavior of TSS in IUWS will be provided in the modelling approach for TSS deposition and erosion in detention tanks based on the hydraulic model and definition of TSS; TSS transport in a sewer and mass balance equation in the junction. The parameters of the simplified models are calibrated using a detailed simulator as a virtual reality. The least square fitting index is used to measure the goodness of approximation of the simplified model.

Simplified Modelling of Detention Tank

A detention tank has the capacity to collect water based on the volume difference between upstream (Q_{in}: m^3/s) and downstream (Q_{out}: m^3/s) as shown in Figure 1. The hydraulic model of the detention tank can be written as:

$$V(k+1) = V(k) + \Delta t(Q_{in}(k) - Q_{out}(k)) \tag{1}$$

where V is the water volume in the detention tank, k is the time and Δt is the time step.

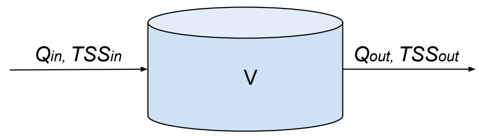


Figure 1. This is a simple graph of detention tank. It shows the topology among volume (V), upstream (Q_in, TSS_in) and downstream (Q_out, TSS_out).

Assuming M and TSS are total mass and concentration of suspended solids respectively, $TSS_{in}(g/m^3)$ and $TSS_{out}(g/m^3)$ are the input and output of TSS in the tank, the simplified M can be presented as:

$$M(k+1) = (1-\alpha)M(k) + \Delta t(Q_{in}(k)TSS_{in}(k) - Q_{out}(k)TSS_{out}(k)) \tag{2}$$

where α is a parameter taking values between -1 and 1 to represent sedimentation or erosion effects in the tank.

Then, according to the physical definition of TSS, the concentration of suspended solids in the tank, and also in the outlets is (valid for $V > 0$):

$$TSS_{out}(k+1) = \frac{M(k+1)}{V(k+1)} \tag{3}$$

Simplified Modelling of Sewers

Based on the hydraulic model of tanks as presented in equation (1), a sewer trunk in IUWS can be assumed as a water tank container which collects water based on volumetric difference between upstream and downstream (Cembrano et al., 2004; Puig et al., 2009). The transport model of water volume is inspired from linear reservoir model, which assumes that the flow downstream of the sewer or catchment is proportional to the collected volume at the time. Then, the dynamics of a hydraulic transport in a sewer will be expressed as:

$$V(k+1) = V(k) + \Delta t(Q_{in}(k) - cV(k)) \tag{4a}$$
$$Q_{out}(k) = cV(k) \tag{4b}$$

where c is a proportional value between 0 and 1.

In a sewer trunk, mass conservation does not apply because of solid settlement and erosion. In order to generalize transport model of TSS, an intermediate variable X with no direct physical meaning is used, leading to:

$$X(k+1) = X(k) + \Delta t(TSS_{in}(k) - c_0X(k)) \tag{5a}$$
$$TSS_{out}(k) = c_0X(k) \tag{5b}$$

where c_0 is a calibration value between 0 and 1.

After combining the equation (5a) and (5b), the following TSS dynamic model in a sewer is produced:

$$TSS_{out}(k+1) = (1-c_0)TSS_{out}(k) + c_0 TSS_{in}(k) \tag{6}$$

By considering that the two coefficients of TSS_{out} and TSS_{in} are independent, a generalization of model (6) can be derived as follows:

$$TSS_{out}(k+1) = c_1 TSS_{out}(k) + c_2 TSS_{in}(k) \tag{7}$$

For each sewer, the parameters c_1 and c_2 need to be calibrated by means of least squares approach using historic or real-time data from telemetry systems, which will be provided in the calibration and validation section.

Model Performance Evaluation

In order to validate and compare implementations of the proposed modelling approaches, the least square fitting index is used to evaluate model performance comparing the simplified model with simulated results produced by lumped model of SWMM-TSS.

$$FC = \sum_{k=1}^{K} (V(k) - R(k))^2 \tag{8}$$

where V means the calibrated value using simplified model and R is the simulated value using SWMM-TSS.

Besides, the fitting rate between the estimation provided by the simplified model and the simulated value with SWMM-TSS is defined using Nash Sutcliffe model efficiency coefficient(Nash and Sutcliffe, 1970):

$$\overline{V} = \frac{\sum_{k=1}^{K} V(k)}{K} \tag{9a}$$

$$FC_{TSS} = 100\left(1 - \frac{\sqrt{\sum_{k=1}^{K}(R(k)-V(k))^2}}{\sqrt{\sum_{k=1}^{K}(R(k)-\overline{V}(k))^2}}\right) \tag{9b}$$

MODELLING TOOLS

The modelling tools used for this work are based on SWMM5, Matlab and the GAMS optimization software (Richard, 2016). In particular, for quality modelling, a new quality model based on SWMM5 (Rossman, 2015) has been developed at LyRE (R+D Centre of Suez) to reproduce TSS transport, sediment accumulation and erosion in sewers (Wiuff, 1985) and retention tanks (Maruejouls et al, 2012), as shown in Figure 2. This quality model uses the extended Barre de Saint Venant equation set from SWMM5.

Figure 2 is the scheme illustrating the modifications made in the SWMM5 library model. White boxes correspond to the existing modules in SWMM5 and grey boxes are for added quality module. WW and DW represent wet and dry weather.

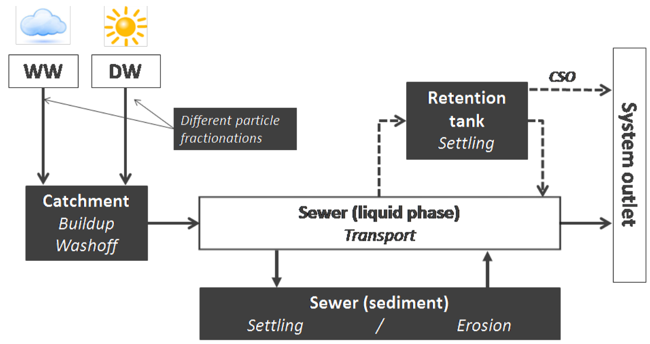


Figure 2. This figure is used to show which modifications were made in SWMM5 model library. The white boxes are existing modules, grey boxes are the added quality modules in SWMM-TSS.

CASE STUDIES

The case studies of the LIFE EFFIDRAIN projects are taken from real systems of Badalona (Spain) and Bordeaux (France). The paper will present results on the Perinot sewer network (Figure 3), which is part of the urban drainage network in Bordeaux Métropole.

The real case study of the sewer of Perinot in Louis Fargue catchment of Bordeaux Metropole covers a total area of 260 ha that is mainly residential. The sewer length is 3 km with an average slope of 0.007, quite constant over the whole catchment. The detention tank is separated in three hydraulically connected volumes for a total storage volume of 35 000 m^3. Even if the slope is generally low, there is no sediment issues on the sewer reported from the operators.

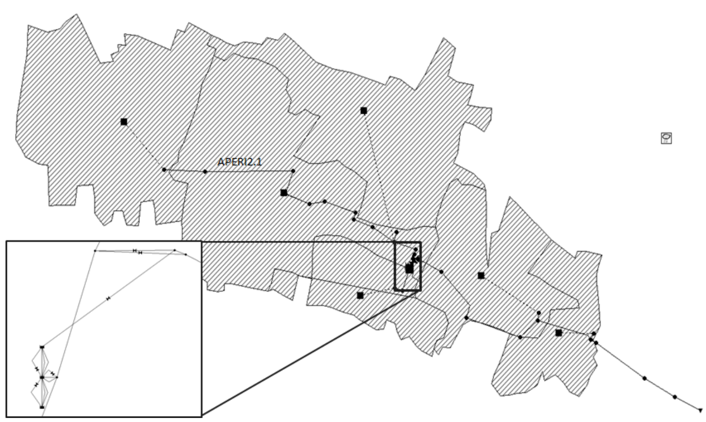


Figure 3. This figure is the topology of Perinot case study.

CALIBRATION AND VALIDATION

Calibration for Simplified Model of Detention Tank

In order to calibrate the proposed simplified modelling approach for detention tank, tank *PER*2 has been selected to produce TSS training data using SWMM-TSS. Rain scenario used for calibration of the simplified models corresponds to the real rainfall measured at Lyon, France in the year of 2007. A rain scenario with 12 hours time stage is selected to produce TSS training data using SWMM-TSS. Setting the sampling and report time of SWMM-TSS as 5 minutes, antecedent dry days as 10 and using the same TSS input (grey color in the figures), TSS outlet from the detention tank has been produced by both SWMM-TSS (black color) and the simplified models (red color) as shown in Figure 4. Comparison has shown that adequate result can be achieved by using simplified model of detention tank with 82.38% fitting rate.

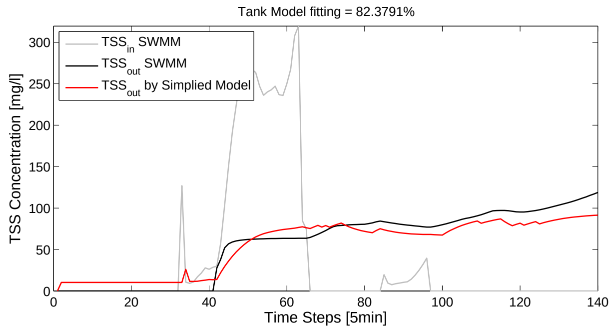
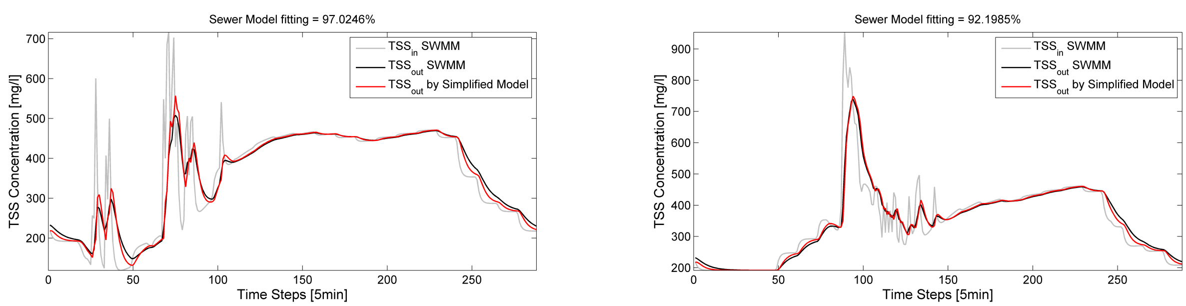


Figure 4. This figure is used to show the calibration performance for the tank model.

Calibration and Validation for Simplified Model of Sewers

One rain scenario from a time stage with 12 hours is selected to produce TSS training data using SWMM-TSS for calibration. After achieving calibrated TSS models, another different rain scenario with different rain intensity is applied in SWMM-TSS to produce TSS data for validating the working of these produced simplified models.



(a) Calibration

(b) Validation

Figure 5. These figures are used to present the calibration and validation performance for the sewer model.

The calibration and validation performances have been shown in Figure 5, which confirm that, the sewer model has considerable performance. Table 1 provides the parameter values after calibration and also the model fitting for both calibration and validation for the sewer model.

Table 1. This table presents the parameters with the calibrated and validation results for sewer models.

	c1	c2	Calibration fitting	Validation fitting
Values	0.73	0.27	97.02%	92.20%

REAL-TIME CONTROL

The integrated management of IUWS (including sewer network and WWTP) requires controlling the flow and TSS in the networks and in-out of detention tanks in real time. The process of IUWS control is also highly dependent on rainfall scenarios which require rain predictions. Considering these characteristic of IUWS control, MPC has been proved to provide efficient methods to control urban drainage networks, generating optimal control actions by optimizing an objective function at every control step. Besides, MPC can predict future behavior of the system through using an internal model over a finite prediction horizon (Cembrano et al., 2004).

When applying MPC to IUWS, the system dynamics may be represented by means of state-space equations. MPC state space equation can be presented as (Butler and Schütze, 2005; Xu et al., 2013):

$$x_t(k+1) = f(x_t(k), u(k), d(k)) \tag{10}$$

where x_t represents water volume and TSS concentrations, u represent the control variables (such as flows through gates or pumps in and out of detention tanks, etc.), d represents the uncontrolled disturbance, related to the rain intensity.

Additionally, the definition of performance indexes related to the quantity and quality of effluents, with the goal of reducing the polluting load to the receiving environment will be applied continued efforts for improving performance of IUWS (Schutze et al. 2002; Schutze et al., 2003; Schutze et al., 2004; Vanrolleghem et al., 2005). More results will be provided during the process of the project.

CONCLUSION

This paper proposed simplified conceptual modelling approaches for representing dynamic behaviors of TSS in sewer networks, which are oriented to be involved in the integrated RTC of IUWS. The SWMM software, with an extension for detailed lumped conceptual modelling of TSS, is used to produce realistic simulated data for calibration and validation. The Perinot sewer network, which is a real life example is used for case study. The application and validation results of the proposed modelling approaches have proved that the simplified conceptual model can capture the main characteristics of TSS evolution in sewer networks with equations that are simple enough to be used for integrated RTC control to IUWS.

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