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Real-Time Control-Oriented Quality Modelling in Combined Urban Drainage Networks ★

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Abstract: Urban drainage networks (UDN) carry urban wastewater to wastewater treatment plants (WWTP) in order to regenerate it before releasing it to the environment. Combined UDN (CUDN) carry both rain and wastewater together, which can overload the UDN and produce combined sewer overflows (CSO) that pollute the environment. Management of CUDN is receiving increasing attention from both researchers and water managers, in order to meet the high quality standards required for water and environment according to EU Water Framework Directive. Due to the complex dynamics of water quality, integrated control of CUDN and WWTP considering both flows and quality of the conveyed wastewater is a difficult problem. In order to design a real-time control (RTC) taking into account hydraulic and quality variables, the use of conceptual quality models is considered as a suitable option. This paper mainly presents a simplified conceptual quality modelling approach to represent the dynamics of suspended solid in sewers of CUDN oriented to real-time control. A sewer simulator implemented in SWMM (Storm Water Management Model) integrated with a lumped conceptual model for total suspended solid (TSS) is used for calibration and validation. A real example of Perinot sewer network is used as a case study. Discussions about RTC implementation in CUDN are also provided in this paper, where Model Predictive Control (MPC) is proposed as the suitable method to control the integrated water and quality models in CUDN as future motivation.

Keywords: CUDN, WWTP, CSO, RTC, conceptual quality model, SWMM, MPC.

1. INTRODUCTION

Combined urban drainage networks (CUDN) are generally designed to convey wastewater flows to treatment facilities in dry weather. During heavy-rain events, as soon as capacities of urban drainage networks (UDN) and Wastewater Treatment Plant (WWTP) are exceeded, mixed water is by-passed to receiving bodies producing combined sewer overflows (CSO), which are identified as polluting hazardous for biological species and ecological status as explained in Becouze et al. (2009); Gasperi et al. (2008). In order to optimize overall objectives of the complete urban drainage system, including the CUDN, the WWTP and the receiving environment, and prevent pollution of the receiving waters, an integrated control of both UDN and WWTP systems is required.

Since 1970s, the potential of using real-time control (RTC) within CUDNs has been discussed in Butler et al. (2005); Schilling (1989). References have proved that RTC is a reliable and cost-effective solution of CUDNs, which can improve the performance of CUDNs minimizing flooding and CSO volumes, thus protecting the environment as presented in Fu et al. (2010); Bulter et al. (2010); Butler et al. (2005); Cembrano et al. (2004); Xu et al. (2013); Beeneken et al. (2013); García et al. (2015). Among real-time control methods, model predictive control (MPC), which can compute optimal control actions taking into account not only the current measurements but also predictive behaviors in a certain horizon, has been successfully tested in water supply and also in the context of advanced urban drainage networks by Cembrano et al. (2004); Puig et al. (2009); Butler et al. (2005); Pleau et al. (2005).

Nevertheless, the majority of RTC applied in CUDN have only focused on hydraulic model and control objectives without considering the polluting quality load inside the carried water, e.g. Cembrano et al. (2004). The few references which consider quality models during the control process mostly use simulation tools to overcome dealing with the complexity of modelling water quality directly. In Rathnayake (2015), control of CUDNs minimizing CSO is achieved by using a non-sorted genetic algorithm (NSGA) linked with storm water management model (SWMM) 5.0. Butler et al. (2005) optimizes integrated modelling of the operation and control of an integrated urban drainage system by developing a simulation package SYNOPSIS which integrates the sewer system (simulated by KOSIM), treatment plant (simulated by IAWPRC) and river model (simulated by DUFLOW) using different softwares.

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For the purpose of operating RTC of integrated urban drainage systems taking into account CSO pollution, appropriate quality models are needed. Such models allow for evaluation of waters according to water quality criteria as in Ahyerre et al. (1998). Because of the input data uncertainty and difficulty in calibration, modelling the generation and transportation of pollution in CUDN during a storm event is complex. There indeed exist some physically-based models which can present quality dynamics in CUDN, but the mathematical equations are difficult to be implemented within RTC as shown in Rouse (1937); Van Rijn (1984); Macke (1980); Ackers and White (1973).

In order to confront these challenges, a simplified conceptual quality modelling approach oriented to RTC for dynamics of total suspended solid (TSS) is presented. The SWMM software (Rossman (2015)) integrated with a lumped conceptual TSS model which depends indirectly on physical parameters through flow and computation of Saint-Venant model, is used to calibrate and validate the modelling approach. A real sewer in Bordeaux, Perinot sewer network is used as a case study.

The remainder of this paper is organized as follows: Section 2 presents the SWMM simulator integrated with a lumped conceptual TSS model, which represents characteristics of solid dynamics in the sewer. Section 3 presents the simplified conceptual quality modelling approach of TSS in sewers, a discussion about RTC applied in CUDN is also provided in the end of Section 3 as motivation of future work. In Section 4, calibration and validation for the proposed simplified modelling approach using SWMM-TSS and the real-life case Perinot sewer network is presented. Section 5 presents the conclusion of this paper.

2. SWMM-TSS BASED ON LUMPED CONCEPTUAL MODEL

As a representative example of sewer pollutants, models for solid concentration and load are presented in this paper, which generally present three dynamic behaviors by Bertrand-Krajewski (2006); Rossman (2015):

- Accumulation of solid sediments over urban catchment;
- Washoff of solid sediments by rainfall;
- Transfer, erosion, deposition of solids in sewer networks and retention tanks.

2.1 Concept of SWMM-TSS

Since solids in sewer are highly driven by hydraulics, a new quality model has been developed based on the SWMM 5 simulator (version SWMM5.1.011) that already includes a detailed description of hydraulics using full Barré de Saint Venant equations. The model library has been modified by adding equations describing solids behavior for the following phenomena:

- **Hydrology**: The exponential build-up model on the catchment was modified to take into account only the impervious area rather than the total area. The washoff model was replaced by the one proposed by Métadier (2011);
- **Sewer**: Accumulation and erosion phenomena are described using Wiuff (1985) energy balance based model used by Bertrand-Krajewski (1993);
- **Storage unit**: Mixing and settling processes are inspired from the work of Briat (1995); Maruéjouls et al. (2012).

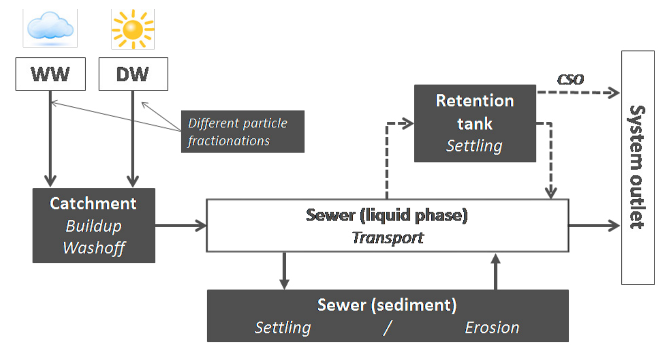

Fig. 1. Modifications made in the SWMM 5 library model

Figure 1 is the scheme illustrating the modifications made in the SWMM 5 library model. White boxes are for existing modules in SWMM 5 and grey boxes are for added quality module.

2.2 Sewer Equations in SWMM-TSS

As previously explained, the main addition in the model library are regarding the sewer accumulation and erosion model. This model is based on Wiuff (1985) that calculates a transport capacity of the flow CT depending on the water ρ_e and particle densities ρ_n, the water velocity U_m and pipe slope I, the particles' settling velocities W_n according to particles' fractions F_{p_n} for each particle classes and the yield coefficient η_n directly dependent on hydraulics characteristics.

$$CT = \frac{\rho_e U_m I}{\sum_{n=1}^{N}\left(\frac{F_{p_n}(\rho_n-\rho_e)W_n}{\rho_n\eta_n}\right)} \quad (1)$$

The CT is compared with the TSS at the pipe inlet to calculate the quantity of TSS that can settle. The erosion model is based on a first order equation dependent on the mass of sediment and a specific erosion coefficient for each particle classes.

3. SIMPLIFIED CONCEPTUAL MODELLING APPROACH

Lumped complex hydrology models work well for simulating real dynamics of TSS in sewer networks, but for the RTC purpose of CUDN, a simple model structure should be presented according to the following principles presented by Norreys and Cluckie (1997); Cluckie et al. (1999); Puig et al. (2009):

- Representativeness of the main dynamics;
- Simplicity, flexibility, expendability and speed;
- Availability of on-line calibration and optimization.

The modelling approaches presented in this paper are designed to be used by RTC to predict the evolution of TSS parameters over a short horizon, which prevent the limitation of classical modelling approaches for temporal measurement campaign. In order to evaluate TSS discharges to the receiving water, performing measurements at the outlet of sewer is the most suitable strategy. The simplified dynamic model of TSS in CUDNs will consider TSS in sewers and mass balance equation in the junctions. TSS behaviors in detention tanks, weirs and also WWTP will be part of future research. The least square function is used to measure performance of these approaches.