Making the best of two Hydrological Flow Routing Models: Nonlinear Outflow-Volume Relationships and Backwater Effects Model

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ABSTRACT

Due to their fast calculation time and computational stability, conceptual flow routing models for sewer pipes are often utilized in the context of integrated urban wastewater modelling. Nevertheless, these approaches have some drawbacks compared to hydrodynamic methods solving the St. Venant equations. In particular the missing consideration of backwater effects can lead to considerable overestimation of peak flows and combined sewer overflow events.

This contribution focuses on verification, comparison and further development of conceptual backwater approaches that aim to overcome the mentioned drawbacks. A new backwater approach from Solvi (2007) is compared with existing backwater approaches implemented in industrial standard conceptual sewer models. Its good approximation of hydrodynamic behaviour was proven and thanks to its explicit upstream storage of retained water it compares favourably to existing backwater approaches. The combination of this approach with a nonlinear conceptual flow routing method results in further improvement.

KEYWORDS

Integrated Urban Wastewater Systems, Mathematical Modelling, Sewer Systems

INTRODUCTION

This paper aims at contributing to the improved modelling of the integrated urban wastewater system (IUWS), aiming at its optimization from an overall perspective (the river's ecohydraulic quality), and not focusing on one of its subsystems separately (i.e. sewer system, wastewater treatment plant and –urban– river). The idea of integrated modelling was already presented in the mid seventies (Beck, 1976) and the first integrated model was applied over 25 years ago (Gujer *et al.*, 1982). However, it took until the early 90s before the concepts started to be disseminated at large (e.g. Triton, 1991; Lijklema *et al.*, 1993; FWR, 1994). Whereas early approaches (Durchschlag *et al.*, 1991) only considered total emissions from sewer system and treatment plant, Rauch and Harremoës (1996), Schütze *et al.* (1996) and Vanrolleghem *et al.* (1996) applied deterministic models to the overall system. These studies revealed the importance of consideration of both, treatment plant effluent and CSO discharges for a proper assessment of impacts of storm events on the receiving water body.

To improve the simulation accuracy of integrated urban wastewater system models an increasing number of processes are taken into account, leading to increased computational loads and requirements for model building flexibility (Rauch *et al.*, 2002). This contribution focuses on sewer system modelling and more particularly on the flow routing process, that is underlying the important compromise between computational load and acceptable inaccuracy.

The deterministic modelling of sewer flow routing using hydrodynamic methods (de Saint-Venant equations) has a number of drawbacks, e.g. numerical stability issues and long calculation times. Moreover, from a river perspective it may not always be necessary to calculate the flow in every single pipe in the system. Often the simulation of input-output behaviour at certain important points can be sufficient. In this case, simplified conceptual models are useful. Most conceptual models are based on the Nash cascade, which models flow in subcatchments by conceptually routing it through a series of linear reservoirs (Viessman *et al.*, 1989). In this cascade, the input of the downstream tank is formed by the output of the previous tank. Figure 1 visualizes the reservoir cascade concept.

The approach behind the hydrological calculation methods is that the pipe is modelled as a "black-box" model, i.e. the water transport is described by an empirically determined transfer function. Thus, the physical processes in the pipe are not exactly represented. The Saint-Venant continuity equation is replaced by a mass balance (1) and its momentum equation by a linear flow-volume relationship (2). The result is an ordinary differential equation:

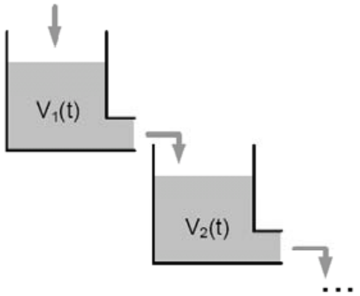

Figure 1 Reservoir cascade concept

$$\frac{dV}{dt} = Q_{in}(t) - Q_{out}(t) \qquad (1)$$

$$Q_{out}(t) = \frac{1}{k} \cdot V(t) \qquad (2)$$

where Q_{in} represents the inflow [m³/s], Q_{out} the outflow [m³/s], V the volume in a certain stretch [m³] and k the so-called retention constant [s].

The required model parameters, i.e. the number of reservoirs n necessary to describe a sewer pipe and the retention constant k, which is the time the water lasts in one tank, can be determined from the physical properties of the pipe (e.g. Kalinin-Miljukov approach modified for pipe flow (Euler, 1983)). The hydrological methods only calculate the flow, the influence of the water level on the outflow of the pipe is not considered. For this reason special situations like backwater or pressurized flows cannot be directly taken into account.

An alternative formulation for flow propagation through sewer pipes is using a nonlinear formulation of the outflow-volume relationship (2). The approach developed by Mehler (2000) replaces the cascade of n linear reservoirs by a single reservoir with a nonlinear function (figure 2, right) that can be calculated from the filling degree τ of the pipe, directly calculated from the geometry of the pipe (see figure 2,left), and the flow carried by a fully filled pipe Q_{full}, calculated with the Prandtl-Colebrook equation. Given the discrete time formulation of model (1) in most softwares implementing conceptual models, a piece-wise linear approximation of the nonlinear relation is required for numerical reasons.

A number of solutions have been proposed to deal with these issues and the objective of the work reported in this paper is to evaluate these proposals and come up with a modelling approach that can handle them. In particular the paper evaluates two methods to deal with the backwater issue, the combiner-splitter approach of Solvi *et al.* (2005) and the retention capacity and storage method implemented in the SMUSI model (Muschalla *et al.*, 2006).

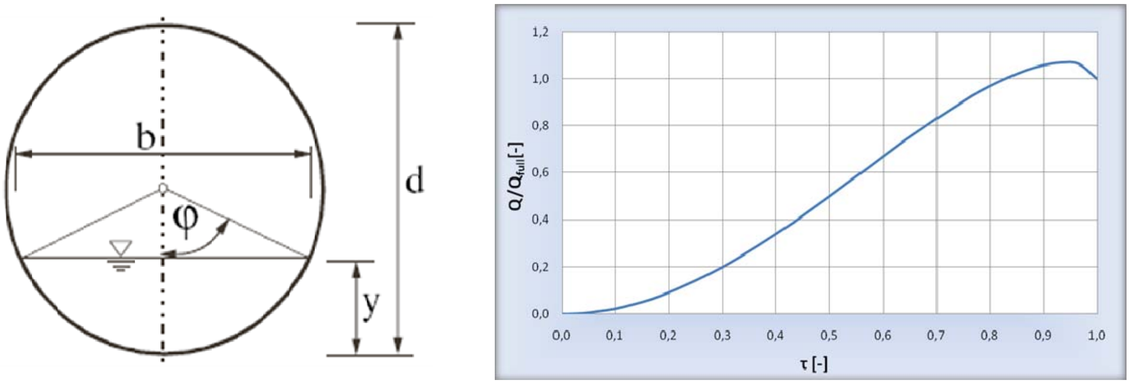

Figure 2 Geometrical characteristics and evolution of the relative discharge of a partially filled circular cross-section.

Finally, a solution is being proposed that takes advantage of the nonlinear formulation of the flow-volume relationship (2) as proposed by Muschalla *et al.* (2006) and the combiner-splitter approach of Solvi *et al.* (2005).

The paper is outlined as follows. First, independent implementations of the linear reservoir model in a continuous ODE-based (WEST) and a discrete time step-based environment (SMUSI) were compared and confronted with a hydrodynamic flow routing model solving the full St. Venant equations. The case study on which this comparison was conducted was taken from ATV-A 128 (ATV, 1992) because it has been used for many benchmarking exercises and provides an interesting number of sewer modelling problems to be dealt with. In a second section, the two backwater approaches are introduced and their implementations evaluated using the abovementioned case study. Finally, the combination of the nonlinear flow routing model and the combiner-splitter approach is tested and its potential discussed.

MATERIALS AND METHODS

For these purposes the hydrological sewer models KOSIM-WEST® (Solvi, 2007) and SMUSI (Muschalla et al., 2006) and the hydrodynamic modelling software SWMM (EPA, 2008) were used in the study. The case study applied in this contribution is taken out of the German guideline ATV-A 128 (ATV, 1992).

KOSIM-WEST®

The KOSIM-WEST® model is derived from the KOSIM modelling tool (ITWH, 2000, Paulsen, 1987) and has been implemented by Meirlaen (2002) and Solvi (2007) into WEST® (Vanhooren *et al.*, 2003). It is designed for long-term simulations of dry weather generation, rainfall-runoff from the surface and transport in the sewer system. It is possible to evaluate both water quantity (flow) and water quality (pollutant loads) inside the combined sewer system and its effluent going to the WWTP or its overflow leaving directly into the receiving water. Beside water the model contains each of the following components in particulate and soluble fractions: chemical oxygen demand (COD), nitrogen and phosphorus. The model is able to simulate pollutant loads of these components in response to individual rain events. The aim of the translation from the KOSIM model to WEST® has been to create a tool to simulate the flow and pollutant loads of the urban drainage in an integrated view, i.e. also including WWTP and river. To this end, the discrete timestep equations behind the conceptual KOSIM modelling tool had to be transformed to the underlying ordinary differential equations so that they can be combined with other submodels of the IUWS and numerically solved by the solvers contained in WEST®. Simplifications of the model are that no evaporation is taking place during rain events, pollutants stem only from impervious surfaces, infiltrated water is clean and surface flow times are the same for pervious and impervious surfaces.

SMUSI

The version of SMUSI used in this study is the research version SMUSI 5.0 (Muschalla et al., 2006). It is a detailed hydrological deterministic rainfall-runoff and pollution load model which is based on discrete time step equations. It simulates the dominant characteristics like pollutant loads, amount of discharged water, duration and frequency of discharge, which are needed for the assessment of the effect of overflow structures on receiving water bodies. The simulated processes include runoff formation and concentration from pervious and impervious areas, superposition of dry weather flow and stormwater runoff in collecting pipes and structures as well as translation and retention of hydrographs and pollutographs in the sewer system (Muschalla *et al.*, 2006). SMUSI models the pollutant components TSS (total suspended solids), BOD (biological oxygen demand), COD (chemical oxygen demand), TOC (total organic carbon), ammonia (NH_4-N) and orthophosphate (PO_4-P).

SWMM

The EPA Storm Water Management Model SWMM (EPA, 2008) is a dynamic rainfall-runoff simulation model used for single event or continuous simulation of runoff quantity and quality from urban areas primarily. It allows applying external flows and water quality inputs from surface runoff, groundwater interflow, rainfall-dependent infiltration/inflow, dry weather sanitary flow, and user-defined inflows. For flow routing either kinematic wave or full dynamic wave flow routing methods (explicitly solving the full de Saint-Venant equations) can be utilized. Therefore it enables to model various flow regimes, such as backwater, surcharging, reverse flow, and surface ponding. The quality part allows modelling any number of user-defined water quality constituents. Especially dry-weather pollutant build-up over different land uses, pollutant washoff from specific land uses during storm events and routing of water quality constituents through the drainage system has been included. In addition, the reduction in constituent concentration through treatment in storage units or by natural processes in pipes and channels can be considered.

ATV-A 128 case study

The case study applied in this work is taken out of the German guideline ATV-A 128. Figure 3(left) illustrates the drainage area schematically. It consists of six subcatchments, five of which are drained with a combined sewer system. Subcatchment 5 is a drainage area with a separate sewer system. Its sanitary sewer discharges into the main collector of subcatchment 6. A storage tank STT with a volume of 2000 m^3 and a throttle discharge of 100 l/s is located after subcatchment 1. Two combined sewer overflows (CSO1, throttle of 50 l/s, and CSO2, throttle of 105.5 l/s) discharge the subcatchments 2 and 3. Subcatchment 4 leads into a by-pass tank BPT with a volume of 180 m^3 and a throttle discharge of 12.3 l/s. The outflows of all rain retention basins combined with the wastewater of subcatchment 5, flow in the main collector of subcatchment 6 and from there in a pass-through tank PTT. This tank has a volume of 1200 m^3 and a throttle discharge of 98 l/s which corresponds with the inflow of the wastewater treatment plant. More details can be found in ATV (1992).

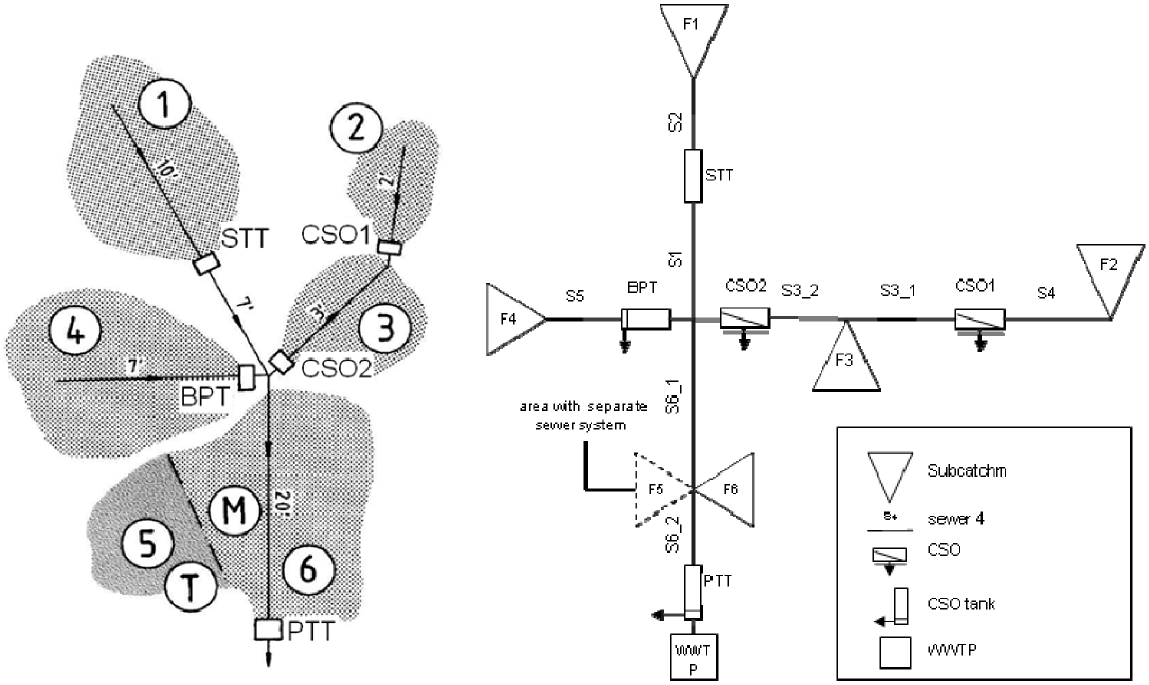

Figure 3 Schematic plan of the drainage area (left) and detailed system plan of the drainage network used to test the backwater effect models (right), modified after ATV (1992).

In the simplified representation of the drainage network in this case study only three main collectors (S1, S3 and S6) are retained. With this simplified system it is not possible to test backwater effects, because the simplified representation of the drainage area does not provide the pipes with its volume and geometry required for the conceptual backflow models in SMUSI and KOSIM WEST®. Therefore, it is necessary to place a pipe above all retention basins and following each point of discharge of all subcatchments. Based on the detailed system information also provided by the A128 guideline, the pipes S2, S4 and S5 were added to the simplified model and the pipes S3 and S6 were each split into two pipes (Figure 3,right).

RESULTS AND DISCUSSION

The work on hydrological flow routing models focuses on three elements. First, a comparison is made between implementations of the reservoir concept in a discrete time and a continuous time simulation platform. This set the basis for subsequent work in the two simulation platforms regarding two backwater modelling approaches for conceptual models. Third, the performance of a method that combines two methods so far implemented seperately in the two simulation platforms is tested.

Continuous versus discrete solution of conceptual hydrological routing model

The discrete time KOSIM and SMUSI models have been around for quite some time. Having such hydrological model available in a continuous time simulator for IUWS modelling, which means that one has to go back to the underlying ordinary differential equations (ODE), was only recently achieved with the implementation of KOSIM into the WEST® simulator (Solvi, 2007). Whereas comparisons between the original KOSIM and its ODE counterpart had of course been conducted by Solvi, the project that led to the results reported here, allowed making a truly independent verification of the implementation. Hence, similarly to the work done on WWTP simulators (Copp *et al.*, 2008), the ATV case study's benchmarking capabilities were taken advantage of to check whether a continuous implementation gives the same simulation results as the more widely used discrete time implementation.

Figure 4 clearly illustrates the finding that SMUSI and KOSIM-WEST® deliver almost the same results with the standard hydrological approaches, when backwater effects are not considered. The small differences are due to the different solving methods in the simulators. Hence, the implementation of the KOSIM model is successfully tested against the similar hydrological rainfall-runoff modelling software SMUSI. Figure 4 also shows that for high rain intensities the overflows were strongly overestimated by the hydrological models (compared to SWMM) due to the non-consideration of backwater effects occurring in the studied system. Hence, it was confirmed that backwater effects have a significant influence on sewer performance assessments and it is essential to take them into account.

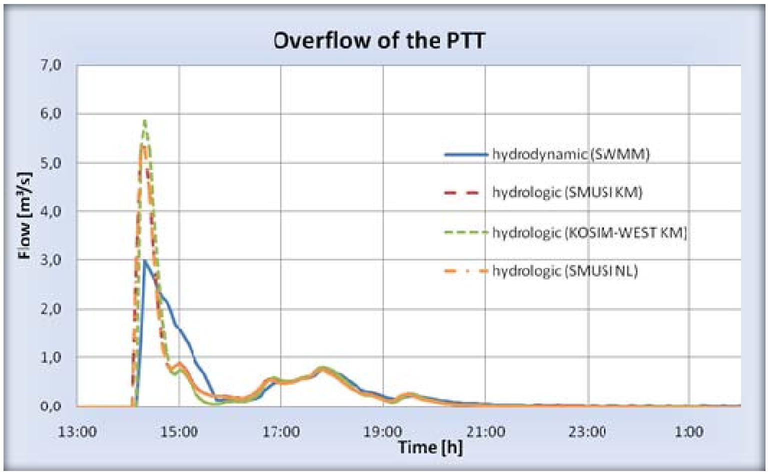

Figure 4 Comparison of the combined sewer overflow of the PTT for the "heavy" rain event

Backwater effects

Modelling approaches

According to Engel (1994) the term backwater describes the situation that the maximum pipe flow is not sufficient to conduct the incoming flow downstream. The excess water gets stored in the adverse direction of the flow by filling the retention volume that can be activated in the pipe located upstream. In case there is no more retention volume available and the water head rises above the top ground surface, a flood arises. Too small pipes, an obstructing structure downstream as well as a throttle can induce backwater. These sewer properties have to be included in a sewer model, especially in a flat sewer system, because backwater can on the one hand induce CSO events at upstream structures that have a significant impact on the river water quality. On the other hand backwater can activate storage volume in the sewer and therefore reduce CSO peaks. As already mentioned, backwater effects taking place in the sewer system are typically not considered in hydrological models. These models thus tend to overestimate flow maxima due to the non-consideration of the retention volume in pipes lying upstream and the non-recognition of overloaded collectors. In this case the CSO frequency and volume are also assessed too high. Hence the need to upgrade these hydrological models by adding a conceptual backwater model without losing the advantage of fast calculation times.

The backwater model developed in KOSIM-WEST® (Solvi *et al.*, 2005) consists of a combiner-splitter combination which is located on top of the tank cascade representing the pipe (Figure 5). The splitter only allows the defined maximum outflow capacity Q_{back} to flow to the collector downstream while any excess water is sent back to the upstream combiner. The combiner adds the incoming flow and the backwater, making that water is getting stored in the volume upstream the splitter. Using a sequence of such splitter-combiners allows having the backwater phenomenon to move upstream.

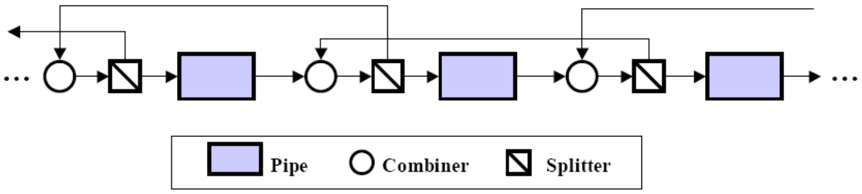

Figure 5 Backflow model implemented in KOSIM-WEST® (Solvi *et al.*, 2005)

SMUSI's backwater modelling approach considers that the water level in a sewer system under backwater conditions, provoked by a rainwater retention structure, is regarded as nearly horizontal upstreamt the structure. Then the retention capacity, which can be activated inside the pipes lying upstream, is determined by a horizontal section through the above lying system. This activated volume is then added to the storage volume of the structure. For this method geometric characteristics of the pipe are needed.

Evaluation results

The effects of the backwater-models will be explained by using the inflow and overflow curve of the PTT as example. These hydrographs are illustrated in Figure 6.

The activation of the backwater model in SMUSI leads to a considerable dampening of the maximum of the overflow curve compared to the simulations with disabled backwater model. So, the retention behaviour of the sewer system upstream of the PTT is represented better, but nevertheless the maximum of the discharge wave is still 40 percent higher than the SWMM results. To improve the performance it would be necessary to enlarge the calculated activatable storage volume, so that the retention behaviour can be simulated closer to reality. Note that SMUSI's backwater model has no direct influence on the inflow hydrograph as the virtual storage volume is added at the overflow structure.

The maximum pipe flow in SMUSI's nonlinear transport model is limited to the flow through the completely filled pipe S6_2 with Q_{full} = 2081 l/s. For this reason the inflow and also the overflow of the PTT is lower than in SWMM, where pressurized flow occurs. The excess water gets virtually stored in the pipe until the flow rate in the pipe is again lower than Q_{full}. Then this stored water is released. The volume of the discharged water is in the same range as in SWMM, but the timing and the maximum value strongly differ. This can be improved by adapting the nonlinear transfer function of the transport model by calibration against the SWMM model as described below for the KOSIM-WEST® approach.

The best fit of the inflow as well as the overflow curve to the SWMM-results is reached with the combiner-splitter backflow model in KOSIM-WEST®. For this the flow rate in pipe S6_2 is limited to the maximum flow rate calculated with SWMM. The virtual storage effect of the excess water in the pipe is the same as in SMUSI using the nonlinear transport model with limited maximum pipe flow, with the difference that the threshold for the beginning of the storage lies higher (taken from SWMM instead using flowrate at completely filled pipe). Hence, not only the discharged water volume, but also the temporal appearance and the maximum value of the discharge wave are assessed in the same range as in SWMM. Even though SMUSI's nonlinear approach can be calibrated in a similar way as KOSIM-WEST®'s combiner-splitter backflow model, only the latter approach allows having the backwater phenomenon to move upstream.

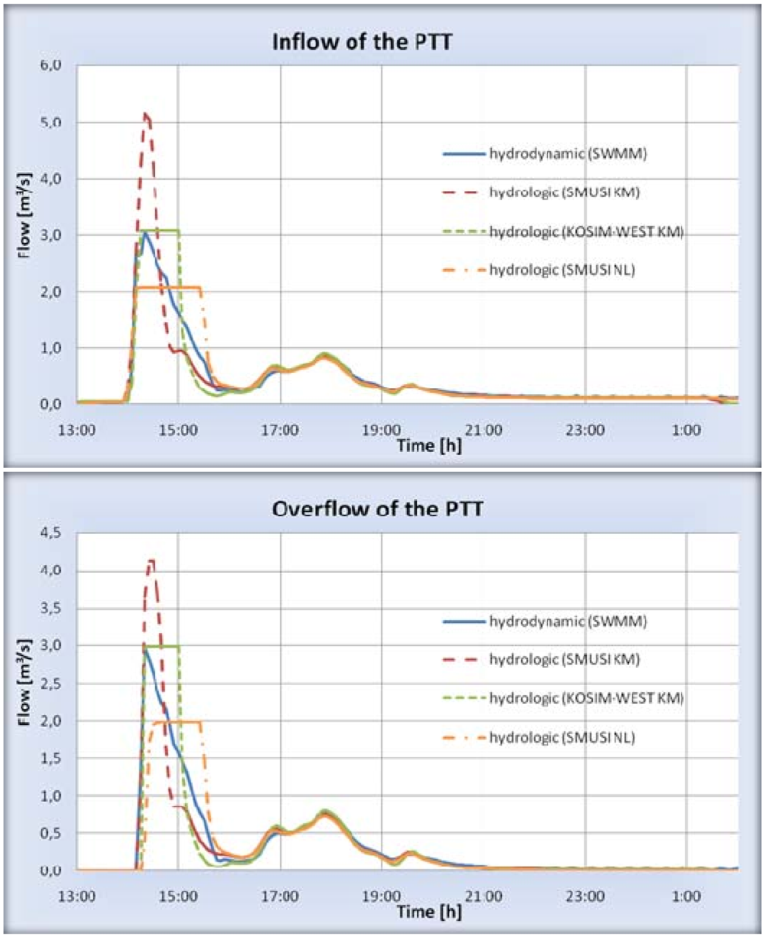

Figure 6 Comparison of the inflow and overflow of the PTT for the "heavy" rain event

<u>Proposed model</u>

Combining all the above, the following model is proposed for numerically efficient, conceptual modelling of sewer systems with backwater by a continuous time simulation environment such as KOSIM-WEST®. SMUSI's nonlinear approach for the flow routing process replaces the Kalinin-Miljukov approach in KOSIM-WEST®, where it can be utilized together with Solvi's combiner-splitter backflow model. While intrinsically identical in model behaviour, the replacement of a set of n linear equations by a single nonlinear one leads to a considerable simplification of the model, because the pipe is now considered as one tank with a nonlinear outflow-volume relationship. For instance in the ATV-example the number of tanks is reduced from 55 to 6, meaning that the number of differential equations to be solved has decreased from 55 to 6. Note that the nonlinear approach also allows to define an outflow-volume relationship for volumes larger than the completely filled pipe, including a pressurized flow ($Q_{max} > Q_{full}$), further enhancing the realism of this flow routing model. Figure 7 illustrates the use of this combined model to more closely describe the hydrodynamically calculated flow evolution in comparison with the original nonlinear implementations. Notice in Figure 7 that the original nonlinear implementation in KOSIM-WEST® is giving identical results as the SMUSI implementation, confirming a verified implementation of the model.

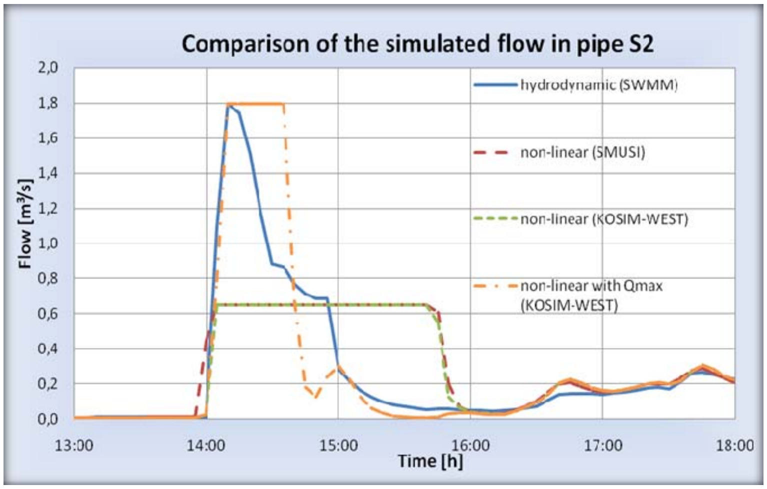

Figure 7 Comparison of the simulated flow in pipe S2 for the “heavy” rain event

CONCLUSION

This paper has evaluated and combined a number of recent developments in conceptual hydrological modelling of sewer systems in view of more efficient integrated urban wastewater system modelling. By using a nonlinear pipe filling level – outflow relationship a numerically much more efficient approach can be provided for continuous time implementations of conceptual models, reducing the number of differential equations by an order of magnitude. Two proposals for backwater effect description were tested and it was found that the simple combiner-splitter backflow-model of Solvi (2007) provides the better results regarding discharged water volume, flow dynamics and the peak of the discharge wave in comparison to the SWMM-results. Only the maximum flow obtained in the SWMM model needs to be specified in the splitter model, even allowing to reproduce pressurized flow in a convenient way.

The whole was verified by double, independent implementations in two hydrological model implementations, SMUSI and KOSIM-WEST® and was applied to a benchmark case study provided in the ATV 128 design rules (ATV, 1992). Comparison with a SWMM implementation of the system showed that the applied modifications (nonlinear transport model and combiner-splitter backwater model) allow taking into account backwater effects and reaching good results with decreased calculation time.

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