# FAST, PARALLEL SIMULATION OF THE INTEGRATED URBAN WASTEWATER SYSTEM

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ABSTRACT

In the presented work, three problems in integrated urban wastewater modelling (sewers, treatment plant and receiving waters) are tackled. The first problem is the fact that the state-of-the-art models of the subsystems use different variables to describe the aquatic system (e.g. BOD, COD, TOC, … to describe organic pollution). This problem is tackled by developing consistent translators from the variables of one sub-model to the variables of another. Secondly, the hydraulic equations, which describe flow propagation in sewer pipes and rivers (the 'de Saint-Venant' equations), are non-linear partial differential equations. These require complex numerical algorithms for their solution, making the models slow and thus difficult to use for optimisation studies. This problem is dealt with by simplifying the models describing the hydraulic behaviour of the system. For the sewer system a catchment run-off model analogous to the Kosim model is used, while for the river model a tanks-in-series model is chosen. When calibrated on a sufficient amount of data, these simplified models are known to be sufficiently accurate in describing the system. These data can be collected during measuring campaigns or, alternatively, be generated with a complex hydraulic model (based on the 'de Saint-Venant' equations). Thirdly, the state-of-the-art models are typically implemented in different software packages, making parallel simulations difficult to achieve. This has been solved by implementing the models of the three subsystems into a single software package, WEST®. This package was developed to enter models by the user. The first models were developed for simulation of wastewater treatment plants. Now these models have been extended with models both for the sewer and the river systems, making integration straightforward. This also enables parallel integrated real time control studies to be carried out.

## INTRODUCTION

The urban wastewater system (sewer, treatment works and receiving waters) as a whole has received increasing attention in the last decades. The first and second edition of the UPM manual (FWR, 1994 and 1998) are the result of the growing concern about the impact of the urban drainage system on the receiving water quality. Integrated models have been shown to be very useful tools to judge the effect of different management options on the water quality, which can be evaluated on the basis of different standards (Fundamental intermittent standard based on concentration, frequency and duration, derived intermittent standards, 99-percentiles, etc…).

The impact on the quality of the receiving water of the urban wastewater system is mainly due to discharges of combined sewer overflows (CSO) during storms and due to the effluents of the treatment plants. This impact can be minimised by applying real time control on the sewer system and/or on the treatment plants. Different studies show the beneficial effect of these control actions (among others, Entem *et al.*, 1998; Petruck *et al.*, 1998). However, (Rauch and Harremoës, 1999) have shown that minimising the total overflow volume does not necessarily result in the best water quality possible. It therefore seems to be necessary to take into account the resulting river water quality when determining the control actions, rather than starting from the traditional emission point of view . To do so, a parallel model of the integrated system is necessary. Schütze et al. (1998) describe the SYNOPSIS simulator, which uses different existing models in different software packages. The communication between the software packages is taken care of by various interface routines , but is fairly complex. On the other hand, , in the present implementation of SYNOPSIS, only the sewer system and the treatment plant run in parallel, while the river model is run sequentially afterwards. Taylor et al. (2000) recently described an integrated catchment simulator, which is able of modelling the three subsystems in parallel, by automation of the communication between the Mouse, Stoat and Mike models. The work described in this paper attempts to integrate the three models in one package, WEST (Hemmis NV, Kortrijk, Belgium), thus it is avoiding problems of file or data transfer and simulating the entire system in parallel.

## RESULTS

### Connecting different models

When developing a dynamic integrated model of the urban wastewater system, it is a logical step to try to combine existing models of the different sub-components, in order not to reinvent the wheel. However, connecting together different models in different software packages is not a straightforward process, since these different models are characterised by separate historical development and are, therefore, not designed for being used jointly. Existing sewer models (like Mousetrap or Hydroworks) or river models (ISIS, MIKE11, etc…) use Biochemical Oxygen Demand (BOD) to describe organic pollution and oxygen demand. On the other hand, the state-of-the-art wastewater treatment plant models (ASM1 (Henze et al, 1987), ASM2(d), (Henze et al. 1995), ASM3 (Gujer et al., 1999)) use Chemical Oxygen Demand (COD) as variable to describe oxygen demanding organic matter. The relationship between BOD and COD is complex and probably different in different situations. Another problem arising when performing measurement campaigns is the detection limit for BOD and COD analysis. It is known that only Total Organic Carbon (TOC) can be measured in very low concentrations (Stowa, 1998). Hence, when dealing with unpolluted waters, BOD or COD measurements may be practically impossible, while the consecutive conversion of TOC to BOD or COD causes difficulties again.

The IWA task group on river water quality modelling, has, in order to address this problem more fundamentally, developed a new river model (RM1), which uses COD as a measure for organic pollution and has moreover closed mass and elemental balances (Shanahan et al., 2000; Reichert et al, 2000; Vanrolleghem et al., 2000). These closed elemental balances mean that the number of e.g. carbon atoms in the system remains constant. Hence, coupling with the ASM models should be easier than with the traditional water quality models. However, differences between the respective state variables still remain and are summarised in Table 1.

In order to keep the mass and elemental balances closed in the integrated model, a connector model is proposed that converts the states of the ASM1 and the RM1 and that maintains closed mass and elemental balances. However, in order to achieve this, it was necessary to assume a certain constant chemical composition of the ASM1 variables. It was found that some state variables can be linked to each other easily, while others require some more attention. Particulate material that is biodegradable according to ASM1 ($X_S$) will also remain biodegradable in riverine conditions. Biomass translation is less evident. The fate of biomass coming out of the treatment plant is uncertain because completely different conditions occur in the receiving water. A fraction of the activated sludge biomass will probably remain active, whereas another fraction is expected to die and has, therefore, to be divided in a biodegradable and an inert part. Once the organic compounds are translated, elemental balances have to be closed. Sink terms are used as compensation between the elemental contents in the ASM1 and the RM1. Soluble COD is used as a sink term for carbon, while the other elements have inorganic representatives in the RM1 ($H^+$, $HPO_4^{--}$. $NH_4^+$, $O_2$). For more details, see Meirlaen *et al*. (in preparation).

Table 1: Comparison of the components between the ASM1 and RM1 models

| **ASM1 (Henze et al.,1987)** Total: 13 state variables | | **RM1 (Reichert et al., 2000)** Total: 24 state variables |
|---|---|---|
| | **Unchanged variables** | |
| $S_S$ | Readily biodegradable material | $S_S$ |
| $X_I$ | Inert suspended organic matter | $X_I$ |
| $X_S$ | Slowly biodegradable material | $X_S$ |
| $S_O$ | Dissolved oxygen | $S_{O2}$ |
| $X_{B,H}$ | Heterotrophic biomass | $X_H$ |
| $S_I$ | Inert soluble organic matter | $S_I$ |
| | **Distributed variables** | |
| $S_{NH}$ | Ammonium | $S_{NH4}$ & $S_{NH3}$ |
| $S_{NO}$ | Soluble oxidised nitrogen | $S_{NO2}$ & $S_{NO3}$ |
| $S_{ALK}$ | Total alkalinity | $S_{CO2}$ , $S_{HCO3}$ , $S_{CO3}$ , $S_H$ & $S_{OH}$ |
| $X_{B,A}$ | Autotrophic biomass | $X_{N1}$ & $X_{N2}$ |
| | **Variables of the ASM1 not included in the RM1** | |
| $X_P$ | Particulate products arising from biomass decay | |
| $S_{ND}$ | Soluble organic nitrogen | |
| $X_{ND}$ | Particulate biodegradable nitrogen | |
| | **New variables in the RM1** | |
| | Dissolved $Ca^{2+}$ ions | $S_{Ca}$ |
| | Algae | $X_{ALG}$ |
| | Consumers | $X_{CON}$ |
| | Dissolved anorganic phosphorus | $S_{HPO4}$ & $S_{H2PO4}$ |
| | Phosphate adsorbed to particles | $X_P$ |
| | Particulate inorganic material | $X_{II}$ |

## Simplifying hydraulics

The state of the art software packages in sewer modelling (Hydroworks, Mouse, …) use very detailed information in order to predict flow routing. A lot of information is needed (on pipes diameters, slopes, roughness, ...) to create these models. The basic equations for flow in pipes are the 'de Saint-Venant' equations, which are, in the complete form, partial differential equations, which cannot be solved easily and thus require complex numerical algorithms to solve them, resulting in a high computational burden of these models.

Therefore, simplified models are needed in integrated modelling and especially in integrated optimisation, which might follow an integrated modelling study. Kosim, which is a German software package, describes run-off and flow propagation in the sewer system of each subcatchment by means of a Nash-Cascade and a transportation time (Paulsen, 1986; iwth

1995). This model makes a number of simplifications when compared to the more detailed models, but is, once calibrated, capable of predicting overflow volumes and peak discharges reasonably well compared to the more detailed models (Fronteau, 1999) and it has already been used by Schütze et al. (1998) in the SYNOPSIS tool to do integrated optimisation studies. On the other hand, calculation times for these types of models are much shorter when compared to the detailed models. Hence, it was decided to use a Kosim-like approach when implementing an integrated model (Schütze et al., 1998).

For wastewater treatment plants, a series of tanks is typically adopted to mimic the hydraulics, and the 'de Saint-Venant' equations are not necessary (De Clercq et al., 1999). Consequently, the mixing hydraulic models are not the limiting factor on the calculation times, and hence do not need to be simplified in order to improve simulation speed.

On the contrary, the flow propagation in rivers is typically described by the 'de Saint-Venant' equations. Because a number of conditions have to be met (uniform slopes, roughness, …) for appropriate use of this model, the river reach under study is typically split into different sections in which these conditions hold. However, the problems encountered in the sewer system, i.e. computational burden and numerical stability, may be encountered too when trying to apply these models. As an alternative, flow routing in rivers can be approximated by a series of tanks with variable volume (Beck and Young, 1975). When these tanks are also used to describe the solutes in the river, then the model is also able to describe dispersion in a reasonably accurate way (Reda, 1996). Moreover, when a biological conversion model is used to predict the conversions taking place in the river, a series of continuously stirred reactors can be used to model river water quality.

The procedure of calibrating a series of tanks model on data generated by the 'de Saint-Venant' equations is illustrated in a case study performed on the river Zwalm (Belgium). A tanks-in-series-model, which was calibrated and validated on the basis of data generated by a full hydraulic model, using the kinematic wave approximation of the 'de Saint-Venant' equations as implemented in Aquasim (Reichert, 1994). The results of the dynamic simulation (Fig 1A.) indicate that the tanks in series model can be used to approximate a complex hydraulic model reasonably well. However, when looking into a bit more detail, it can be seen that the tanks-in-series-model (implemented in WEST®) predicts a flowrate increase a bit too early compared to the complex hydraulic model. However, the approximation was found to be sufficiently close to the complex model. Most importantly, the simulation time of the tanks-in-series model was three times shorter than the simulation time of the kinematic wave approximation of the ’de Saint-Venant’ equations. More details can be found in Meirlaen et al.

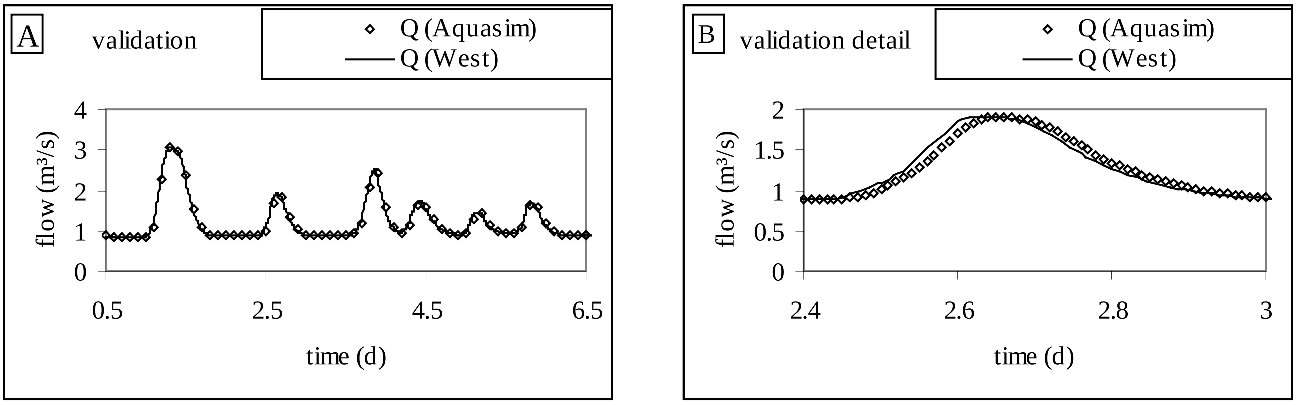


**Figure 1: The validation results of the river Zwalm**

(2000). In this work and in Meirlaen et al. (in preparation) it was also shown that a tanks in series model can not only be used to model flood wave propagation, but also to model dispersion in a 26 km long river stretch. Hence, a tanks-in-series model can be accepted as a reasonable alternative to a complex hydraulic model in certain cases, but needs to be calibrated against a sufficient amount of generated data. Hence these models are considered mechanistic surrogate models, as opposed to complex mechanistic models. These surrogates form an approximate substitute of the complex mechanistic model, which is considered to represent reality.

## Implementation of the integrated model in WEST®

All models discussed above (the connector between Kosim and ASM1 or RM1, and the connector between ASM1 and RM1, the Kosim equations, the wastewater treatment plant models, the tanks-in-series model) have been implemented in WEST®. Within WEST®, the first developed models described the behaviour of wastewater treatment plants. As a result, all the state of the art models for modelling activated sludge plants (ASM models, different primary and secondary clarifier models, …) were already available in this software. Due to the open structure of WEST®, and due to the fact that Model Specification Language (MSL-code) , which is used within WEST to define models, is an open language and is easy to understand and learn, the existing modelbase could be extended with models of the other parts of the integrated urban drainage system.

The RM1 model (Reichert et al., 2000) and the connector between the ASM1 and the RM1 (Meirlaen et al., in preparation) have been implemented. The models are built in such a way that an efficient reuse of the models will be possible. For example, when implementing the RM1 or a modified version thereof, only the stoichiometry and the kinetic Peterson matrix have to be added to the modelbase in order to use it for description of a river system (including hydraulics). The coupling with ASM1 showed to be more complicated, but still was not too difficult. It is felt that the Peterson way of representing models (as in the ASM1 and the RM1) is an easy and compact way of describing biological conversions in aquatic media.

Currently, the basic concepts of the Kosim model are being implemented into the modelbase. This is more complicated than the other implementations, because the Kosim equations are written in discrete form, while the numerical engine in WEST® is only capable of solving algebraic and differential equations. Hence, all difference equations of the Kosim model need to be transformed into differential equations, which was not always straightforward. Another problem encountered in the implementation of the Kosim model is the so-called translation in pipes. The transport between the different sub-catchment in Kosim is approximated by a shift in time (e.g. what came in 20 min ago, is now coming out). This translation requires the simulator to keep track of the data up to a certain time lag in the past (in simulated time). This is a feature that was originally not available in WEST®, but is currently being implemented. The way a Kosim basin with a three tanks Nash-Cascade is implemented in WEST® is shown in Fig. 2. It can be seen that the three tanks in the Nash-Cascade are explicitly present in the graphical representation of the model. Other model components generate dry weather flow, calculate evaporation, or act as input for the model.

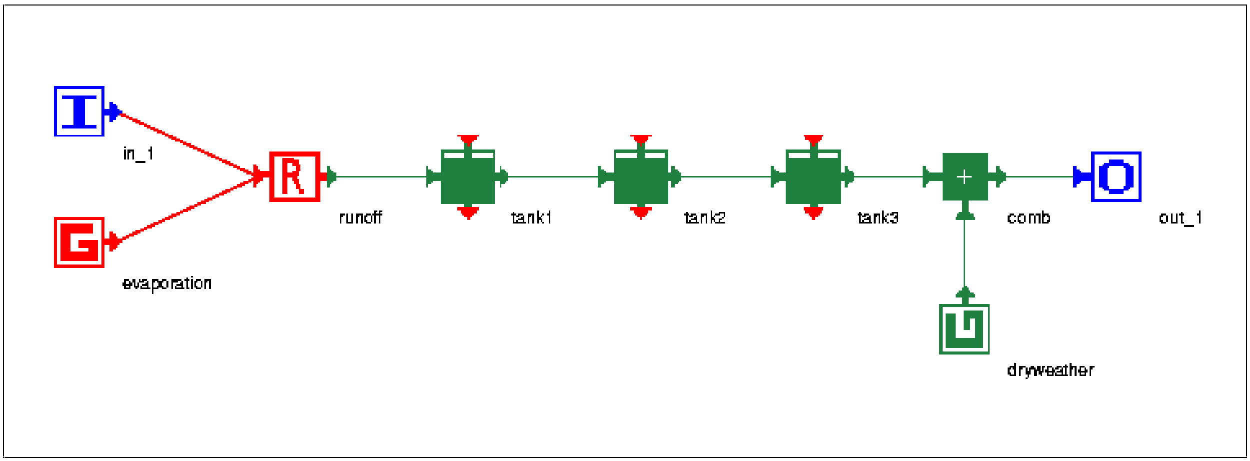


**Figure 2: Implementation of a Kosim subcatchment**

## Integration

WEST® is a package that allows hierarchical modelling, and hence an integrated model might look very simple, as more detailed models are hidden under the different components of the overall model (Figure 3). In this way, all models can be developed and tested separately, while the linking can be done afterwards without any problems. Controllers, which use the state of the river to modify setpoints in the wastewater treatment plant, can be added and, hence, integrated control becomes possible.

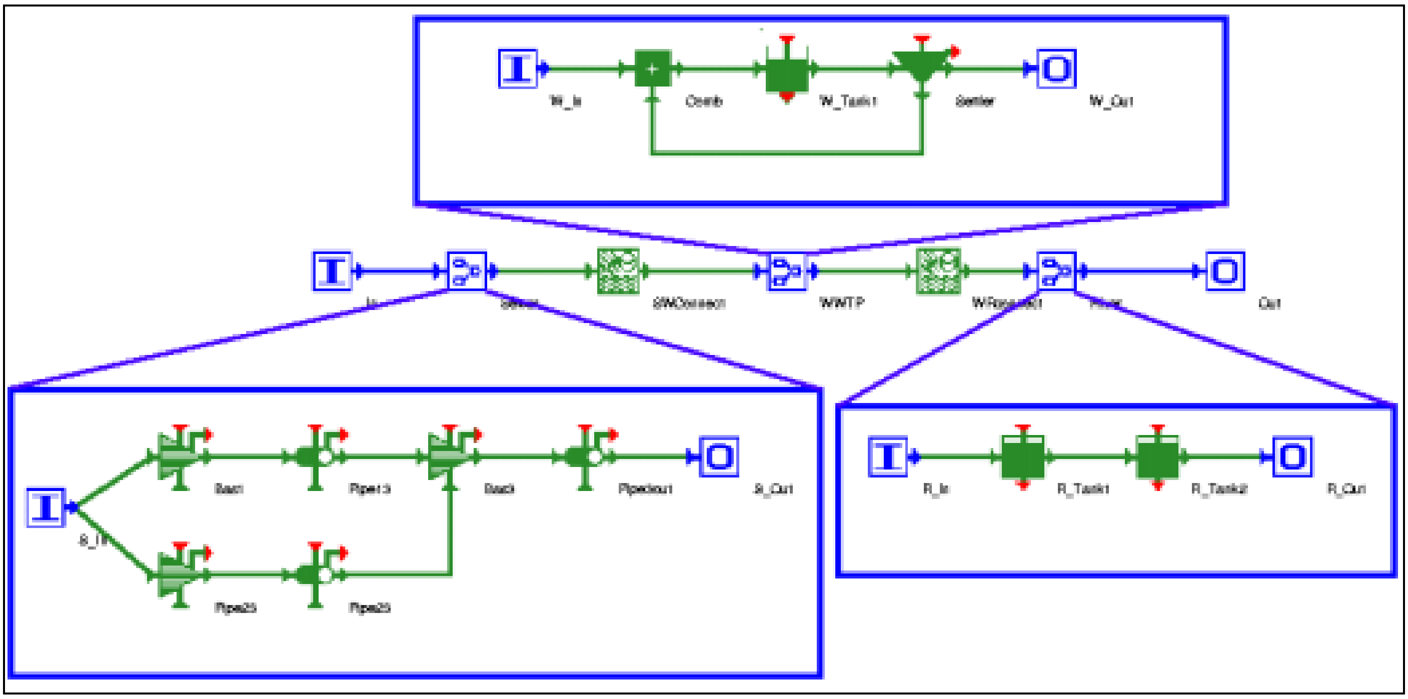


**Figure 3: Integrated model in WEST®, revealing the complexity of the subcomponents**

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