Integrated urban catchment modelling for a sewer-treatment-river system

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ABSTRACT
River water quality can be improved by optimising the urban wastewater system management through integrated operation of the transport and the treatment of these waters. Mathematical models are then useful tools to understand and explore the system in question. They allow to test various operating strategies and to see their effects on the long term. In this study of a river catchment in Luxembourg, the WEST® software is used as the modelling and simulation platform for the whole integrated system. It already contains standard models for WWTP and river processes. For surface runoff and sewer transport, the KOSIM hydrological model was implemented into the WEST® model-base. The implementation was thoroughly verified by comparing simulation results from both softwares. Also, backwater effects are taken into account through a conceptual model of backflows and results are compared to hydrodynamic results obtained with the Infoworks™ CS software. These are then used to calibrate the former.

KEYWORDS
Backwater effect; integrated modelling; urban wastewater; Water Framework Directive

INTRODUCTION
During the last decade, analysis and modelling of integrated sewer-wastewater treatment plant (WWTP)-river systems have gained considerable interest in urban wastewater management (e.g. Meirlaen *et al.*, 2001, Vanrolleghem *et al.*, 2005, Schütze *et al.*, 2003). The management from a receiving water's perspective is one of the key principles underlying the adopted EU Water Framework Directive (CEC, 2000), which asks member states to adopt measures to reach a 'good' chemical and ecological status for both surface and ground-waters. Indeed, goals such as improving receiving river water quality along with reducing sewer and WWTP operating costs require integrated studies, as sewer and WWTP both have impact on the river and do not work with maximum efficiency towards river quality when considered independently. Hence, the mutual interactions between these three subsystems and the effects they have on each other need to be studied.

Mathematical modelling of the integrated urban wastewater system (IUWS) allows detailed system analysis and can eventually give answers to questions regarding for example the origin and quantity of pollution into the receiving river, stemming either from the WWTP or, during wet weather conditions, from the combined sewer overflows (CSOs). However, it is not a trivial task to build such a model, first of all due to the complexity of the integrated system and therefore the model itself, and secondly due to the difficulty for the user to choose the appropriate sub-models for the integrated model out of a multitude of possible options (Rauch *et al.*, 2002). The choice then depends on the availability or not of data and the objectives of the study in question (e.g. Willems, 2003). As a main guidance, the model should be as detailed as necessary and as simple as possible to achieve the best objective driven results (Meirlaen et al., 2001).

Linkage difficulties at the interfaces between the subsystems (Benedetti *et al.*, 2004, Vanrolleghem *et al.*, 2004) and data transfer problems between sub-models during simulations are a problem, and it is therefore useful to be working with a single simulation tool for all subsystems. In this case study, WEST® (Hemmis N.V., Kortrijk, Belgium, Vanhooren *et al.*, 2003) is used as software platform. It gives the possibility of adding models to those already present, like the IWA standard activated sludge models (Henze *et al.*, 2000) and river water quality model (RWQM1, Shanahan *et al.*, 2001) for the WWTP and the river respectively. For surface runoff and sewer transport, the hydrological model underlying the KOSIM software (ITWH GmbH, Hanover, Germany) was implemented into WEST® (hereafter referred as KOSIM-WEST).

The ultimate aim of the presented case study is the development of operational strategies for sewer and WWTP in order to minimise nutrient concentrations in the considered eutrophied river. Impact assessment is done through long-term simulations with regard to relevant components like COD, ammonia and orthophosphates. The adopted methodology and approaches to build an integrated model in order to achieve those goals are presented in this article. Also, a method to calibrate the hydrological sewer model using an Infoworks™ CS model is explained.

KOSIM-WEST

The implementation of the KOSIM model into WEST®

The implementation of the KOSIM hydrological catchment runoff and sewer transport model into WEST® was already ongoing (Meirlaen, 2002) and was completed recently within this project. The mathematical expressions inside KOSIM are recursive discrete time step equations (ITWH, 2000) which have been transformed into the underlying ordinary differential equations (ODEs) so that they can be numerically solved by the solvers contained in WEST®. Modelled variables are water, soluble and particulate COD, ammonia and orthophosphates. The model blocks currently available are catchments (for runoff and dry weather generation), collectors (for transport) and basins (for retention). Specialisation of these models to fulfil the user’s needs is possible. Pollutant loads are modelled as the sum of a daily concentration pattern for dry weather flow (DWF) plus a constant load from surface runoff of rainwater. However, in order to take into account first flush concentrations, linear accumulation and exponential wash-off (Ashley *et al.*, 2004) of particulate COD were added as an option. Another feature that has been put into KOSIM-WEST is the simulation of backflows, which are described in more detail in a dedicated section.

The implementation has been verified with the original KOSIM software for a hypothetical system consisting of a 20ha large catchment, a 200m^3 tank and a 700m long collector. Simulation outputs for flow and pollution from both softwares have been compared for the three sub-models. The rain input data used were taken from KOSIM examples and the input parameters needed are the same due to the fact that the model concepts are identical.

Simulations were performed for a low intensity rain event and a moderate rain event. Curves for the catchment outflow overlap well as depicted in Figure 1. A plot of the relative error shows that differences increase with increasing variations of the flow, which is supposed to be due to the different solving methods of the softwares: fixed time steps for KOSIM against varying time steps for numerical solving of ODEs in WEST® (smaller time steps are used when important dynamics occur). The mass balances were verified, and to make sure that the initial conditions are the same in both softwares, simulations start two weeks before the comparison is done. Monthly results show less than 0.5% mass differences, even in months with heavier rain events; such mass unbalances are due to differences in peak amplitudes.

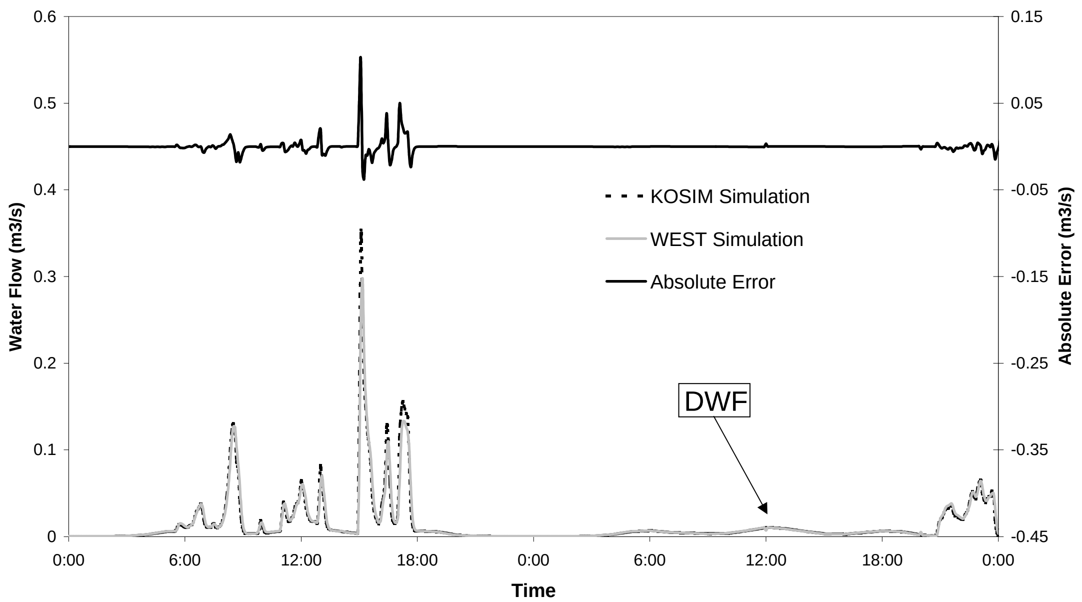

Figure 1. KOSIM and WEST® simulation results for water outflow from a hypothetical catchment for a moderate rain event.

KOSIM and KOSIM-WEST compared

Although the concept behind both softwares KOSIM and KOSIM-WEST is identical, their specific features and their general applicability differ strongly. First of all, interception of information on for example wetting losses during runoff is possible in KOSIM-WEST, whereas in KOSIM only flows and pollutant loads can be viewed by the user. Also, the addition of new models for special processes or structures is a useful characteristic of WEST®. However, the computational speed of KOSIM is higher than the one of KOSIM-WEST by an order of 10, and is therefore more suited for some studies, like for example the assessment of a sewer system alone. But, for an integrated study the outweighing advantage of KOSIM-WEST is that it is contained in the same software as models for WWTP and river, so that no data transfer is required during simulations of the whole system.

THE CASE STUDY

General description

A sketch of the case study, situated in the North-East of Luxembourg, is shown in Figure 2 and some of its characteristics are summarised in Table 1.

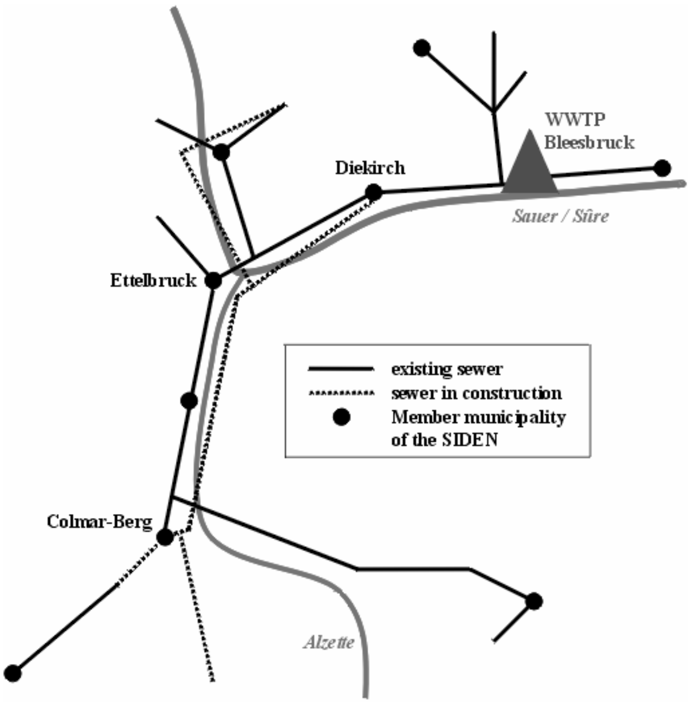

Figure 2: Schematic overview of the catchment 'Bleesbruck'

The river Sûre, with a hydrographic basin of about 4250km^2, crosses Luxembourg from West to East and flows into the river Moselle at the German border. At approximately 25km upstream of the WWTP Bleesbruck, the Sûre is retained by a dam, becoming a drinking water reservoir serving around 70% of Luxembourg's population. Therefore its water quality can be considered as being very good until, near the town of Ettelbruck, it receives the water of the river Alzette. The latter is flowing through highly populated and industrialised areas of Luxembourg, thereby receiving a high quantity of nutrients and pollutants with it.

The WWTP 'Bleesbruck' and its sewer system are operated by the SIDEN (Syndicat intercommunal de dépollution des eaux résiduaires du Nord). In the framework of a European Life project (Schosseler *et al.*, 2003), the functioning of the WWTP has been optimised and therefore the WWTP has been equipped with online sensors for COD, NH_4/NO_3 and PO_4 measurement. Since the second biological treatment step has a smaller capacity as the first one, the WWTP is overloaded, particularly during wet weather flow conditions.

Table 1: Characteristics of the 'Bleesbruck' case study

Catchment	Sewer catchment area: ~ 10km^2 Domestic and industrial discharges: ~ 52,000PE (population equivalent)
Sewer Network	~ 60km (+12km of parallel main collector in construction + future replacement of CSOs by retention basins)
WWTP 'Bleesbruck'	Hydraulic capacity: 100,000PE Pre-treatment (screen, grit removal and grease separation), 2 activated sludge units in series, phosphate precipitation, on-line sensor equipment for nutrients
River 'Sûre'	Flow: 10 – 20m^3/s depending on season Problems: High ammonium and phosphate concentrations

The sewer network drains the wastewater and rain runoff from about 25 rural villages and towns, together with wastewater from various industrial sites (a brewery, a slaughterhouse, a dairy, a tyre industry and a landfill). The network is currently being refurbished with the construction of a parallel, pressurised main collector and with the replacement of CSOs by retention basins. In the present situation, the collector is often hydraulically overloaded and backwater effects with consequent upstream discharges into the river seem to be a reality. Therefore they need to be taken into account by the models.

Modelling approaches

The aims of the study and the data availability. The aims of this study are the identification of influences of the urban wastewater system on the receiving water quality and a consequent immission-based optimisation of the operation of the sewer network and of the WWTP. Different strategies will be tested and compared to one another, using long-term simulations over one or two years. This requires that the model is not excessively complex to avoid too long simulations. Moreover, the more complex the model becomes the more parameters related to local information are required. Especially for catchments, sewer network and river these data are hardly available. Hence, conceptual modelling both for sewer and river seem to be a reasonable approach to fulfil these requirements. However, the model certainly needs to contain the crucial points of the sewer system like pumps and tanks and the biological units of the WWTP. To progressively understand the functioning of the system in question, it was decided to go from simple to more detailed models as more information will become available in the future. Moreover, the simulations of the simplified model will allow for a first localisation of critical zones of pollution within the system or identification of influential parameters. The model can thus be updated and extended where needed.

The model of the current sewer system will be gradually updated along with the actual changes of the system during the new constructions. This way, in view of the river water quality objectives of the EU Water Framework Directive, strategies can be tested on how to optimally use the storage capacities in the network during rain events, and on how to empty basins afterwards, depending on locations of pollutant concentrations in the sewer and the situation at the WWTP. Moreover, as the actual construction works are ongoing, excellent model validation opportunities exist by confronting model predictions of the new system with the actual data collected. The river will be represented by a tank-in-series model; RWQM1 will be used for river water quality. To model the WWTP, an existing calibrated model (Schosseler et al., 2003) will be transferred into WEST®.

A first version of the sewer model. Although not all necessary data is available at the moment, a first version of the sewer model was constructed in WEST®. The elements so far included are the catchments with their population and estimates of impervious and pervious surfaces. These are attached to the main collector, without including overflows and basins as information on their respective locations are not yet known. Industries are not yet represented either, but as the actual interest focuses on the hydraulic runoff, they only become more important when the focus shifts to water quality.

BACKWATER EFFECTS

Backwater effects can occur because of high level of water at the sewer outlet due to river or tide, because of a decrease of discharge capacity from one trunk to the trunk downstream (slope decrease or roughness increase) or due to the presence of an obstructing structure downstream. (Motiee *et al.*, 1997). Hydrological models can however not simulate these phenomena and it seems impossible to find a general function that could describe them

(Sartor, 1999). These backwater flows do nevertheless cause the CSO device upstream to overflow and as the volume of water and pollution loads into the river are vital factors in the impact assessment of the urban wastewater system on the receiving water, fictitious backflows have been added to the collector units of KOSIM-WEST. They allow for overall mass balances of the sewer model to be closer to reality.
A collector is modelled as an *n* tank cascade, each reservoir with retention time *k*, where the parameters *n* and *k* are evaluated according to the Kalinin-Miljukov procedure (ITWH, 2000), using length, diameter, slope and roughness of the pipe. Backflows are modelled using a combiner-splitter combination (see Figure 3): the combiner sums the water coming from the upstream pipe and from the downstream backflow whereas the splitter, according to a given maximum flow Q_{max}, sends any excess water to the upstream combiner.

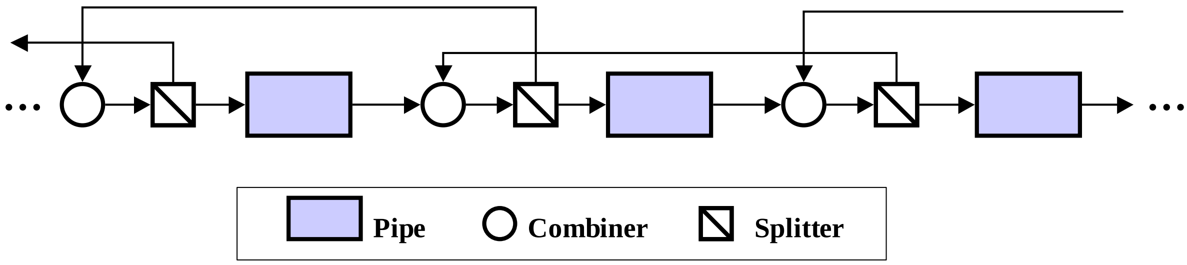

Figure 3: Pipe-combiner-splitter unit to model backflows in WEST®.

The Southern part of the 'Bleesbruck' catchment model is schematically represented in Figure 4. It contains only one overflow device at the beginning of the collector to make sure that backwater effects are happening, but this will be adjusted according to the real system to assess the impact on the river. To find Q_{max} values for each pipe in KOSIM-WEST, an exact copy of this model was created with Infoworks™ CS. The maximum outflows of the pipes of the latter can be used as Q_{max} limits for the KOSIM-WEST pipes. It should be noted that because the models for catchment runoff are not the same in the two softwares and although the catchment outflows do not differ significantly, it was decided to use KOSIM-WEST catchment outflows as inflows to the collector in Infoworks™ CS. This way the method of inspecting differences in flows through the pipes could be more rigorously applied.

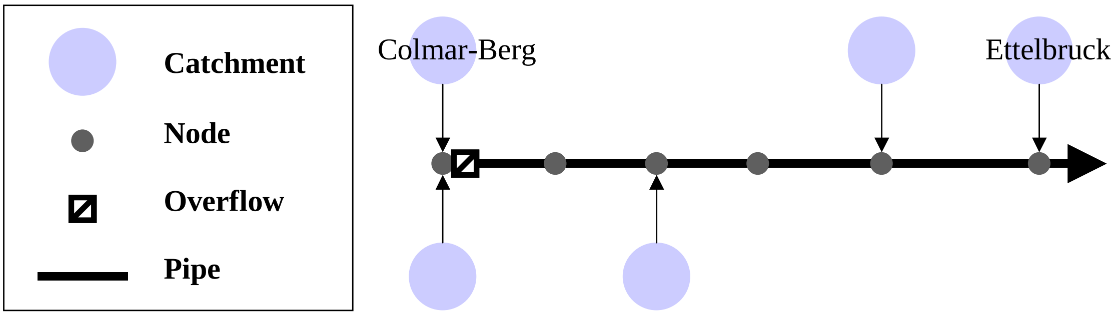

Figure 4: Southern part of the modelled 'Bleesbruck' collector.

Table 2: Mass balances in Infoworks™ CS and WEST® over one year.

		Outflow (%)	Overflow (%)
Infoworks™ CS		81.5	18.5
WEST®	Without backflows	91.3	8.7
	With backflows	83.8	16.2
	With calibration	81.7	18.3

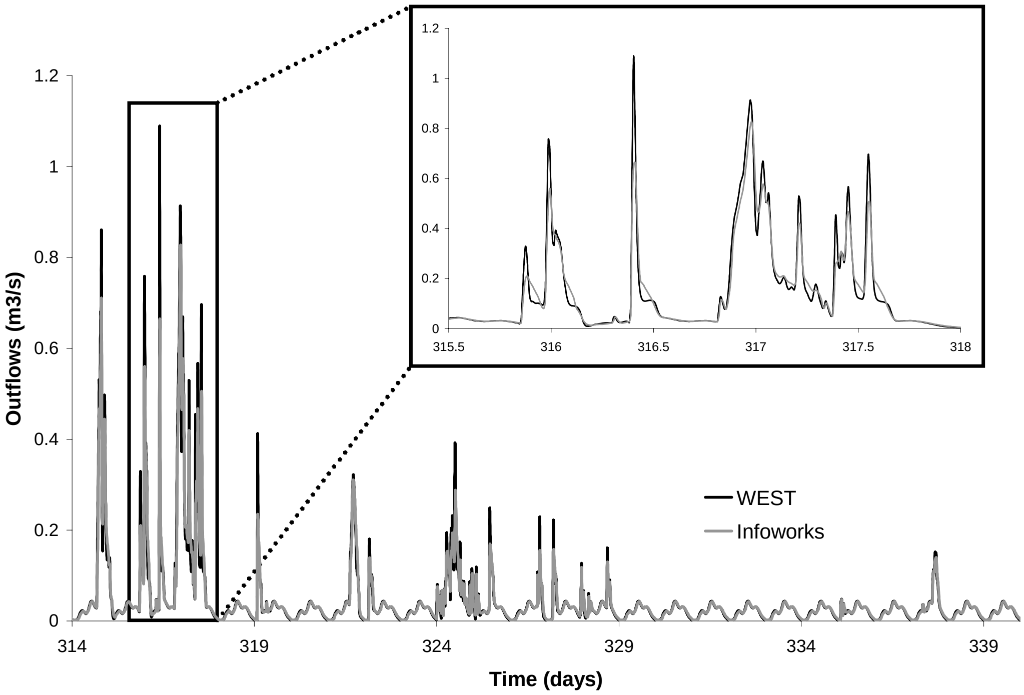

Figure 5: Outflows from the South Bleesbruck catchment in Infoworks™ CS and in WEST®.

Table 2 shows values for simulated outflow volumes. KOSIM-WEST results are given for 3 cases: without backflows, with backflows according to Infoworks™ CS outflows from every pipe, and with calibration of Q_{max} values to further increase backflows. Adjusting Q_{max} values by inspecting outflows in Infoworks™ CS does hence allow getting a good approximation. The fine-tuning method allows to further fit mass balances. It should however be noted that the question arises whether this fine-tuning is really appropriate. In fact, it consists of a decrease of Q_{max}, thereby reducing peak flows. Figure 5 shows the outflows and it can be seen that, generally, a good visual fit is obtained. However, for single events and peaks it is not possible to achieve a complete match. It is important to choose appropriate rain events for the calibration: calibrating with January low intensity rains, the model will not be producing good results for August higher intensity events. This is due to fixed parameters in WEST®, whereas in a hydrodynamic model, flows vary according to pressure and flows upstream. In this case, the model has been calibrated with one-year simulation data as it will be used for long-term simulations and the backflow model is hence an attempt to refine the hydrological model towards better mass balances.

CONCLUSIONS

One of the aims driving the construction and the use of the integrated model presented, is to find a good trade-off between modelling the complexity required for achieving the objectives of the case study, the time available and the quality of the results. The model for the case study will progressively be updated as data become available. For the sewer network, the KOSIM hydrological model was implemented into WEST®, so that one software platform can be used for the whole integrated urban wastewater system model. The developed "conceptual backflow" model is meant to achieve better mass balances in case backwater effects are relevant. It provides the modeller with an additional calibration parameter for flows in the sewer. However, further investigations need to be carried out to explore the limits of such an approach.

A planned measurement campaign in the river will allow the calibration of the river model. By connecting the three submodels, some operating strategies can be developed and tested.

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