Implementation of an integrated model for optimised urban wastewater management in view of better river water quality: A case study.

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Abstract Integrated management of the urban wastewater system requires a holistic consideration of sewer network, treatment plant and receiving water. Modelling and simulation of this integrated system allows for testing scenarios to improve the status and performance of the system. This paper presents a general approach to use such integrated models. The effect of management options is evaluated using emission and immission criteria and the methodology for both model construction and scenario analysis is illustrated with a case study in Luxembourg.

Keywords integrated modelling, scenarios, urban wastewater system

Introduction

Assessment of the integrated urban wastewater system (IUWS), including sewer network, wastewater treatment plant (WWTP) and river, fits into the holistic approach suggested by the Water Framework Directive (WFD) (CEC, 2000), which requires 'good' ecological and chemical quality of surface and groundwater. From this perspective, river water quality becomes an indicator for the performance of sewer network and WWTP, and water quality standards ("immission" based evaluation) with traditional emission regulations make up the "combined approach" required by the WFD.

If a holistic approach is to be implemented through identification of the long-term influences of the urban wastewater system on the status of the receiving water bodies, all processes involved in the fate of urban wastewater, i.e. from urban runoff to emission via combined sewer overflows (CSOs), from wastewater treatment to river water quality, need to be considered. However, when dealing with complex systems like the water cycle, interactions between subsystems are difficult to grasp because there are a multitude of influencing factors and the amount of data needed to assess the behaviour of a system is very high. Modelling and simulation of such an integrated system is a means to transpose our knowledge of that system into predictions of it and bridge the gap between theory and practice.

Implementation of an integrated model has been done in view of various goals. It can be used to test scenarios in order to evaluate future impacts e.g. future housing or increase of drained impervious surfaces, or to assess certain measures meant to improve performance of the system, e.g. treatment volume increase at the WWTP or in-stream aeration of the river (e.g. Frehmann *et al.*, 2002, Vandenberghe *et al.*, 2005). Other applications include evaluation of operating strategies (e.g. Erbe *et al.*, 2002) like influent load increase to the WWTP or for implementation of immission-based real-time-control (RTC) (e.g. Meirlaen *et al.*, 2002; Vanrolleghem *et al.*, 2005a). Overall, problems encountered with integrated model implementation are the heaviness of the model and the data availability. A good overview is given in Rauch *et al.*, 2002.

This paper presents the implementation of an integrated model on a case study in Luxembourg. After a description of the latter, deficits and pressures are identified and the integrated model calibration is briefly described. In the result section, simulated scenarios are presented and assessed both using emission and immission criteria. Although these results are referring to the here described case study, the general methodology is applicable to other studies.

The Case Study

Description

The case study is situated in Luxembourg (see Figure 1), consists of a semi-rural sewer catchment and involves 3 receiving waters with differing water quality. It can be considered as a follow-up project of the European project LIFE98 ENV/L/000582 where an activated sludge wastewater treatment plant (WWTP) has been modernised with tools for real-time monitoring and control of the treatment processes (Schosseler *et al.*, 2000; Schosseler *et al.*, 2003).

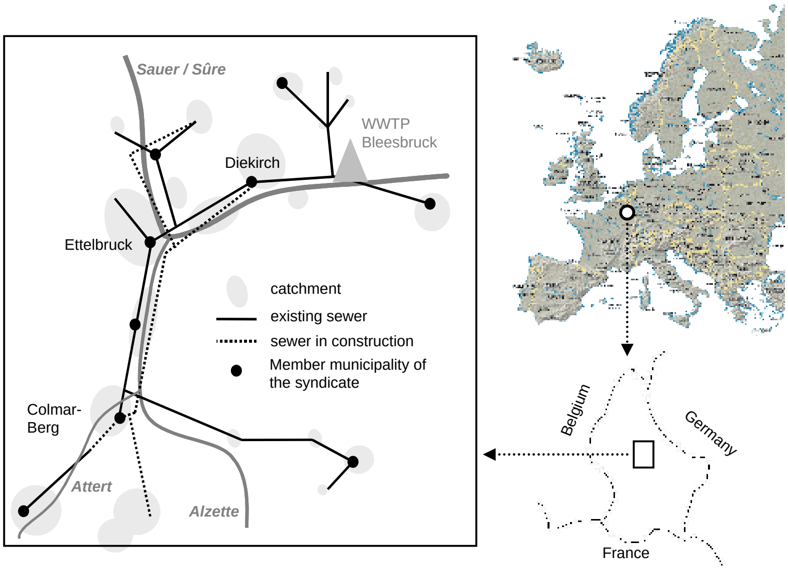

Figure 1: Location and schematic representation of the Luxembourg case study.

In fact, a higher treatment efficiency has been achieved through a model-based analysis and control of the biological treatment processes, based on the input of analytical on-line data.

Two measurement campaigns on WWTP and river water quality have been performed in the frame of the EU project CD4WC (www.CD4WC.org). They each lasted for 2 weeks and took place in June and October 2005. There were 7 measurement locations, 5 in the river and 2 at the WWTP (inflow and outflow). The campaigns consisted of composite daily samples for 12 days and 2 days of intense measurement with 2-hour composite samples. Temperature, conductivity and dissolved oxygen (DO) were measured on-line, while total chemical oxygen demand (COD), soluble COD, biological oxygen demand (BOD), suspended solids (SS), Chlorophyll A, ammonium, nitrate and orthophosphates were analysed in the laboratory.

Pressures, deficits and impacts

Identification of pressures on the receiving waters is a task required by the WFD Common Implementation Strategy. This implies collection of emission data from sewer and WWTP, as well as data giving information on the river status (Borchardt *et al.*, 2003).

Data from sporadic measurements over 5 years from the Luxembourg Water Agency and data from the measurement campaigns mentioned above were analysed to characterise river stretches. It could be confirmed that the good quality of the Sûre deteriorates after mixing with the Alzette. The latter travels through the industrialised and most populated areas of Luxembourg, collecting effluents from many WWTPs and therefore carrying concentrations of often more than 1.5mg/l of ammonium. In summer dissolved oxygen concentrations go below 4mg/l in early morning. Eutrophication is well visible in some of the stretches. Diffuse pollution is difficult to assess as agricultural activity varies and exact data do not exist.

At the WWTP, despite of model-based oxygen control, nitrification is not efficient through low autotroph development due to a too low sludge age. Another cause of bad nitrification is the presence of on/off actuators, not well suited for exact and efficient aeration. Also, phosphate peaks are not well eliminated due to delayed control action so that the effluent contains total phosphorus (TP) and total nitrogen (TN) concentrations above the limits set by the Urban Wastewater Directive (CEC, 1991). Currently a sludge storage volume is being built in order to accept the sludge coming from smaller treatment plants, which are so far just added to the influent as they arrive.

The sewer system is composed of a main collector running along the rivers to gather wastewater from approximately 25000 inhabitants, a dairy, a brewery, a slaughterhouse and 2 commercial areas. Apart from a few storage pipes and 2 local retention basins, no storage volume is available so far. However, construction works are ongoing in the sewer network with the transformation of some CSOs into retention basins and a parallel collector to reduce the discharges into the existing collector, especially as another catchment and industrial area will be connected in the future. Although no measurements can support this, some older overloaded CSOs appear to overflow regularly. This was shown by simulations with the sewer model and confirmed by experience from the operator. Infiltration was evaluated using the 21-day minimum method (Brombach *et al.*, 2002) and ranges from 0.8 l/s/ha to 1.5 l/s/ha in winter and in summer, respectively.

Objectives

The objectives of this study are to identify the weak points of this system using an integrated model and to test possible measures to improve its performance.

The Integrated Model Building and Calibration

Model Building

A model structure and its complexity depend on the goal of the study and on the availability of data. Long-term simulations and scenario analysis require the model not to be excessively complex so that calculation times stay reasonably short, but to comprise all relevant processes for the scenarios to be analysed subsequently. Also, detailed information on catchments and river are often not available and so conceptual models (with fewer parameters to calibrate) appear more suitable to represent the subsystems. Hence, in the river and the sewer pipes, water transport is modelled by a cascade of linear reservoirs. Moreover, model simplification was performed by reducing the number of simulated CSOs and their respective drained surfaces. This was verified through model comparison of the extended and simplified versions (Solvi *et al.*, 2006).

For the sewer catchment and network, an extended version of the KOSIM model (ITWH, 2000) was implemented (Solvi *et al.*, 2005), allowing for simulation of backwater effects and first flush effects through pollutants accumulation and wash-off on the surface and/or sedimentation in pipes and basins. For bio-chemical reactions in the system, a simplified version of the IWA river water quality model RWQM1 (Reichert *et al.*, 2001) and the IWA activated sludge model ASM2d (Henze *et al.*, 2000) are used. The sub-models are connected by means of interface models (Vanrolleghem *et al.*, 2005aa; Vanrolleghem *et al.*, 2005bb), which transform the state variables of one sub-model into the state variables of the following sub-model. The entire sewer-WWTP-river model is implemented in the WEST® simulation software (HEMMIS nv, Belgium) (Vanhooren *et al.*, 2003) and the components of such a model are depicted in Figure 2.

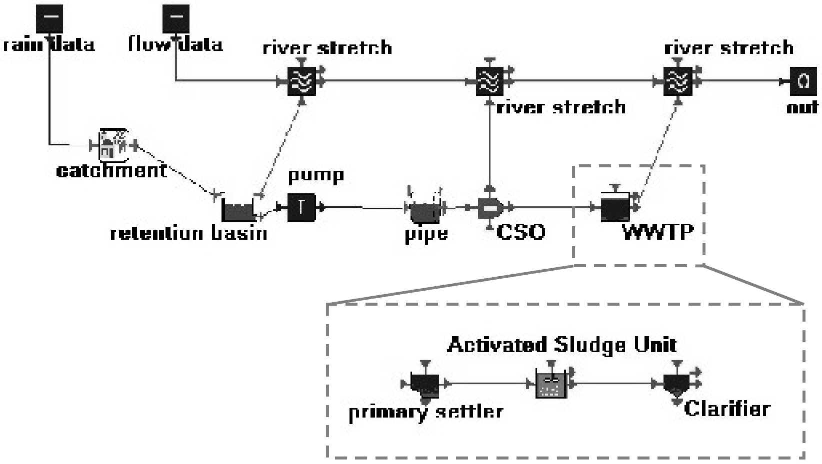

Figure 2: Components of a simplified integrated model in WEST®.

Calibration

Calibration and validation were done for the individual subsystems first. For sewer network and WWTP, one year calibrations were performed, as scenarios are tested for the period between March and October, this time of the year being identified to be the most sensitive for the river. Flows to the WWTP could be calibrated since measurements were available, but overflows at individual catchments could not be adjusted for no measurements were available. The river model was calibrated using the data from the two measurement campaigns. Morphological properties determined model tank subdivisions.

Scenario analysis and discussion

Although the integrated model could not be calibrated for CSO overflows, comparisons between scenarios with respect to the reference case can be performed.

Using the identified pressures and deficits, some scenarios (see Table 1) have been prepared and simulation results were compared, both for emission and immission criteria.

Table 1: List of simulated scenarios with abbreviations for later reference.

Domain	Description of scenario	Abbreviation
Source control	Dry weather flow pattern flattened by buffer tanks at households and industries	FlatDWF
	Dry weather flow pattern for ammonium flattened by urine separation and buffer tanks at households	FlatNH4
	Impervious surface reduction (-25%) by decoupling	ImpRed
	Reduction (-50%) of infiltration by network rehabilitation	InfRed
Construction	Construction of retention basins (1500 m^3)	RetBas
	Increase of nitrification volume (550 m^3)	NitVol
	Construction of incoming sludge buffer tank (100 m^3)	SluBu
Operation	Increase (+33%) of WWTP hydraulic load	OvLo
	Nitrification cascade control with DO controller set-point controlled by NH4 measurements	ImprN
	Improved phosphorus control by reducing dosage delay	ImprP
Other measures	Shading in the river by means of trees plantation along the banks	Sha
	Artificial reaeration in the river after the confluence of Sure and Alzette	Reae

Looking at immissions, the simulation outcomes from the river model, containing 15 tanks in-series for the Sure, were inspected in Tank 7 shortly after the confluence of the Sûre and the Alzette and in Tank 15 after the WWTP effluent (cf. Figure 1). Figure 3 displays simulation outcomes for river DO and ammonia concentrations.

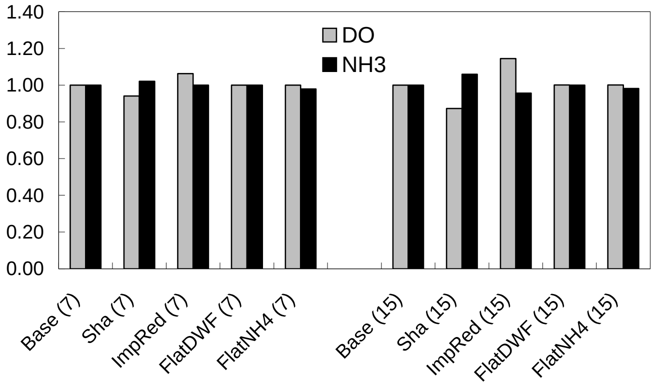

Figure 3: Relative average concentrations for dissolved oxygen (DO) and ammonia in the river (Tank 7 and 15 of the model) for different scenarios.

Overall, most of the simulated scenarios (not all shown here) have little effect on the river. This is probably due to the relatively small hydraulic contribution of WWTP and CSOs (>3%). The option for shading in the river does not seem to be suitable in this case; average DO concentrations decrease and ammonium increase. We also find that exceedances (time fraction above the threshold) of minimum concentrations of DO (4 mg/l) have increased, and maximum/minimum values have decreased. The effect is amplified for Tank 15. The reduction of solar radiation reduces the growth of algae, and therefore also DO concentrations. In Tank 7 the negative effect is less pronounced as the velocity is higher, i.e. there is more reaeration. It seems that a reduction of impervious surfaces, and hence the reduction of overflow volume, has the best effect on river water quality here.

Even if most of the scenarios did not have considerable effect in the river, emissions are important, especially in the vicinity of the overflow. Figure 4 presents results for the emissions from a CSO (normalised to the base case) that is currently being transformed into a retention basin, which actually appears to be a good investment. The latter scenario will have to be investigated for immission in the future.

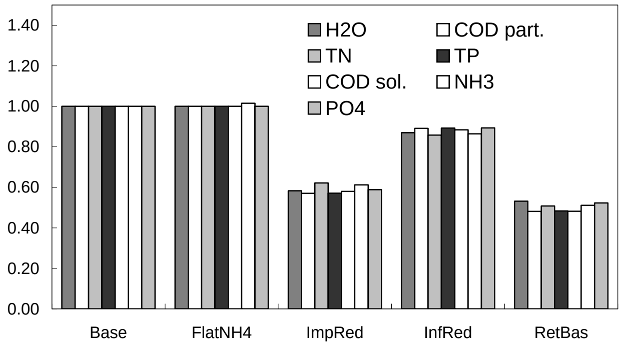

Figure 4: Scenario results at a critical CSO of the catchment, normalised to the base case.

To improve operation of the treatment plant, all scenarios have been tested and outcomes are shown in Figure 5. The nitrification volume option (increasing sludge retention times of the second biology) is beneficial for both nutrients. The infiltration reduction is increasing the outflow concentration for ammonium, but the yearly discharged load is smaller (not shown). A relatively inexpensive but very beneficial measure for reducing ammonia and total phosphorus emission concentrations is the implementation and improvement of control. A feasibility study for the implementation of such a control option will have to be done now. A special case is the overloading scenario as it does not significantly increase the average concentration nor does it affect minima or maxima much. Also, yearly effluent loads are only increased by 5% (not shown), whereas almost 90% of the previously discharged load from the CSO before the WWTP is now treated.

Conclusions

From the scenarios it can be deduced that nutrient impact from the urban wastewater system is small in this case study compared to the pollution coming from upstream the studied river stretch. However, it was noted that the effect of measures on a given river stretch can vary from one to another. Whilst a measure can have a positive effect on one subsystem, it can have a negative one on another subsystem. These links and interactions together with more elaborated control strategies will be analysed in the next part of this project. It should also be noted that the results presented in this paper are based on averages over a year and are not event-based. Local and short-term deficits will be included in the future. Overall, the testing of scenarios allows to deduce the efficiency of a measure before implementing it. This can save money and/or underline the optimisation potential of a change in the system. For model implementation a trade-off between objectives and needed data was found.

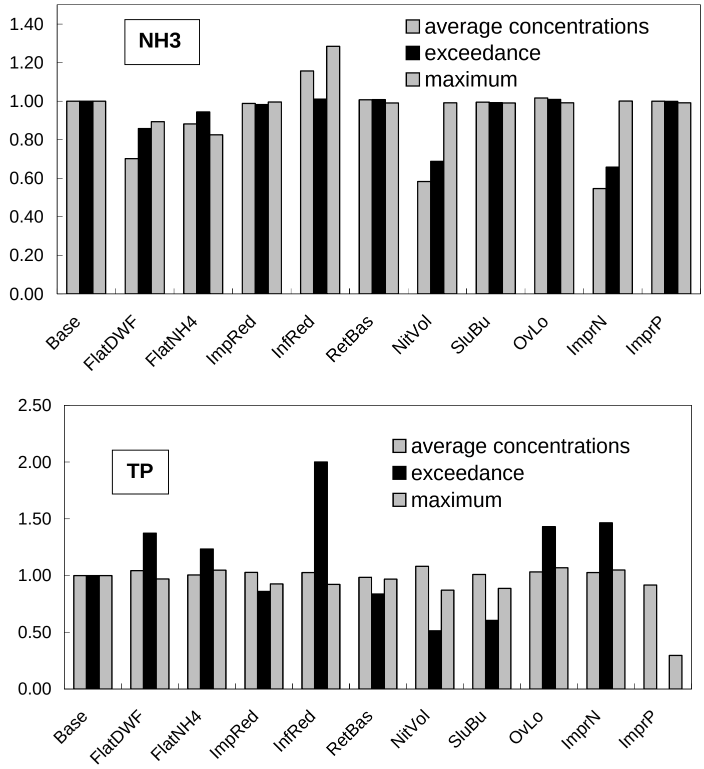

Figure 5: Results of scenarios for WWTP emissions, normalised to the base case. Exceedance thresholds are: NH_3 = 5mg/l, TP = 2mg/l.

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