Dynamic integrated modelling: a case study on the river Lambro

Modélisation dynamique intégrée: un cas d'étude sur la rivière Lambro

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RESUME

L'approche de modélisation intégrée est appliquée sur la rivière Lambro pour une étendue de 26km en aval de la station d'épuration de Mérone (Italie du Nord). L'hydraulique et les processus de qualité sont modélisés par des bassins élémentaires en série. Les simulations pour les sous-modèles utilisés (ASM1 et RWQM1) ont été réalisées dans WEST®. Le but de cette étude est de modéliser les effets de capacité insuffisante au niveau de la station d'épuration sur la qualité de l'eau dans la rivière. Même en temps sec, il y a déviation régulière d'eau usée ce qui mène à un cycle journalier de concentrations de polluants dans la rivière. L'analyse d'une amélioration technique de la station d'épuration a permis d'évaluer les effets bénéfiques sur la qualité de l'eau dans la rivière.

ABSTRACT

In this paper an integrated modelling approach is presented and applied to a 26km stretch of the river Lambro downstream of the Merone WWTP (northern Italy). Hydraulics and quality processes of the Lambro have been modelled with a 'tanks in series' approach. The sub-models used (ASM1 for the treatment plant and RWQM1 for the river) have been implemented in the WEST® simulator. The purpose of this study is to model the effect on river water quality of an insufficient treatment capacity of the WWTP. The plant was constantly working at its maximum hydraulic capacity, leading to a daily bypass of dry weather wastewater, which imposed a marked diurnal cycle in pollutant concentrations in the river. An assessment of the actual WWTP upgrade has been made to evaluate its beneficial effect on the river water quality.

KEYWORDS

ASM1, Integrated modelling, LAS, Model interfaces, RWQM1

1 INTRODUCTION

Integration of the different components of the urban drainage system in a single model allows the better understanding of the working of the system as a whole, and of the mutual interaction between its components. This is clearly essential for the evaluation of the system performance, as well as for the detection of its weak points, in the context of environmentally and economically sound planning and management practices. It is also a necessary step for the implementation of Real Time Control strategies for the urban drainage system (Meirlaen *et al.* 2001).

(Schütze *et al.* 1998) used different existing software packages glued together in the SYNOPSIS tool. The sewer and treatment plant simulation was run in parallel, generating influent files for the river model. However by implementing the system this way, it was not possible to use the water quality of the river in a control loop for the sewer system or treatment plant. (Rauch and Harremoës 1999) used genetic algorithms to optimise the oxygen concentration in the river, but did not use a parallel model in which the current river states can be used to trigger a valve or pump in the drainage system. (Taylor *et al.* 2000) describe the integrated catchment simulator, connecting different existing software packages. Automatic connections and data exchange between different software packages represent a big step forward; however, the used models are hydraulically very detailed, resulting in long calculation times and large output files. Recent examples of integrated parallel modelling on a single software platform can be found in (Meirlaen *et al.* 2001; Schütze *et al.* 2003).

One of the main problems when developing an integrated model is the incompatibility between state variables, processes and parameters used in the different sub-models, e.g. the treatment plant model and the river model, the former being typically based on COD and the latter on BOD like in QUAL2E (Brown and Barnwell 1987). (Maryns and Bauwens 1997) tried to avoid the problem by using the ASM1 model (Henze *et al.* 2000) in riverine conditions but without satisfactory results. To tackle this problem more fundamentally, the IWA task group on river water quality has developed a COD based model, RWQM1 (Reichert *et al.* 2001). The states of this model are more like ASM states, but some differences still remain because the full RWQM1 model has to describe more components than the ASM1 model (e.g. algae growth).

Environmental conditions in sub-systems being rather different, the main processes will also differ because organisms behave differently depending on the environment. For instance, nitrifying bacteria in an activated sludge (AS) system are confronted with a high competition for oxygen with heterotrophic organisms in high concentrations, while in the river system this competition is not that strong. Therefore, when using two models with different state variables, a interface needs to be developed in order to translate the state variables of the original model to the ones of the destination model in a consistent way. This interface needs to contain all available knowledge about the different states in the two models, different environmental conditions in the two sub-systems, and requires closed elemental balances, in this case for COD, C, N, P, O and H.

In this paper an integrated modelling approach is presented and applied to a 26km stretch of the river Lambro downstream of the Merone WWTP (northern Italy). Dispersion and water quality of the Lambro have been modelled with a tanks-in-series approach. The whole system, including sub-models used to describe treatment plant and river in the study area (respectively ASM1 and RWQM1), has been implemented in the WEST® simulator (Vanhooren *et al.* 2003). The purpose of the study is to model the effect on river water quality of an insufficient treatment capacity of the Merone WWTP, which was constantly working at its maximum hydraulic capacity, even so not avoiding the daily bypass of dry weather wastewater, imposing a marked diurnal cycle in pollutant concentrations in the river for a considerable distance downstream the plant. Boron and Linear Alkylbenzene Sulfonate (LAS) have been used respectively as tracer and indicator of pollution. An assessment has been made to evaluate the beneficial effect of the construction of further treatment volumes in the WWTP on the river water quality.

2 METHOD

2.1 The model interface

The interface is a list of algebraic equations expressing concentration inputs in the river in terms of concentration outputs from the sewer or WWTP.

RWQM1 uses COD as a measure for organic pollution, which makes integration with the COD-based ASM models easier. Moreover, RWQM1 has closed mass balances for COD, and closed elemental balances for C, N, P, O and H. Since these are important properties, the goal was to keep these in the new interface.

Some state variables can be easily transformed from the AS to the river conditions. Slowly and readily biodegradable substances will probably remain biodegradable entering the river. Active biomass from the sewer or AS system does not remain active in the river, since environmental conditions in sewer or treatment plant and river are usually very different in terms of temperature, food, light intensity, etc. (therefore these variables may also vary with the period of the year), probably causing inactivity of at least part of the biomass. In the interface, biomass is split in a part that remains active and in inert and slowly biodegradable organic matter.

Autotrophic biomass is modelled as first and second step nitrifiers in RWQM1, but only as one group of organisms in the ASM1. In the interface the incoming autotrophic biomass is split into two active groups (with respective surviving fractions f_{N1} and f_{N2}), while the remaining (dead) part is split into slowly biodegradable and inert particulate organic matter. Parameters for the fractions are to be found by calibration, since so far no values are available in literature, only the relationship $f_{N1}=3{\cdot}f_{N2}$ (Focht and Verstraete 1977) can be useful as a first approximation. Dead biomass is split in two particulate fractions, one biodegradable and one inert, by means of the parameter f_I, analogous to the parameter f_P in ASM1, even if it has to be considered that environmental conditions are different.

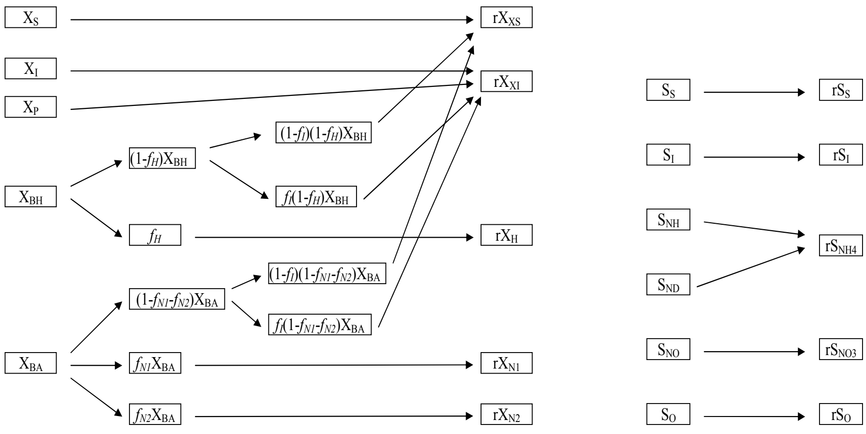

Figure 1: Fate of particulate biomass (left) and of soluble components (right) from state variables of ASM1 to RWQM1

The way in which particulate matter and soluble components is transformed when going from the treatment plant to the river is shown in figure 1. To calculate output concentrations of carbonates (CO_2, HCO_3^- and CO_3^{2-}) in the river model, the carbonate equilibrium equations have been implemented in function of incoming alkalinity (state variable in ASM1) and pH (parameter of the interface). Soluble organic nitrogen (S_{ND} in ASM1) is added to NH_4 in the output, since ammonification is usually fast, and the river model has no similar state. Variables used in RWQM1, but not in ASM1, like nitrite, particulate phosphate or algae are set by fixed parameters, which need to be estimated for the system under study.

After maintaining closed mass balances, elemental balances still need to be closed. This is done using compensation terms, used to compensate for a lack or surplus of elements. To this end, the elemental flux calculated in ASM1 state variables should be compared to the one in RWQM1 state variables. The difference between these two fluxes (either negative or positive) is the compensation term, and is added to the state chosen as balance state for the specific element. Ideally, compensation terms should always be zero. A balance state serves as a sink or source of elements in organic compounds, e.g. if more nitrogen is present in organic matter entering the river than coming from the treatment plant, then the amount of ammonia going into the river is artificially decreased in order to close the nitrogen balance over the interface. The balance states chosen in the river model are carbonates for C, NH_4^+ for N, HPO_4^{2-} for P, DO for O and H^+ for H. To calculate the flux of the five elements coming from ASM1, the composition of the different model components need to be fixed. The N and P content were taken according to (Henze *et al.* 2000), while C, O and H content were taken according to (Reichert *et al.* 2001). The following equation illustrates the use of a compensation term for N (N_{comp}), which in the interface is added to the outgoing NH_4^+ (balance state for N).

$$N_{comp} = \begin{bmatrix} i_{N\_SS} \cdot S_S + i_{N\_SI} \cdot S_I + i_{N\_XBH} \cdot X_{BH} + i_{N\_XBA} \cdot X_{BA} + i_{N\_XP} \cdot X_P \\ -i_{N\_rSS} \cdot rS_S - i_{N\_rSI} \cdot rS_I - i_{N\_rXH} \cdot rX_H - i_{N\_rXN1} \cdot rX_{N1} \\ -i_{N\_rXN2} \cdot rX_{N2} - i_{N\_rXS} \cdot rX_S - i_{N\_rXI} \cdot rX_I \end{bmatrix}$$

or

$$N_{comp} = \sum_{J}^{ASM1} i_{N\_J} \cdot J - \sum_{J}^{RWQM1} i_{N\_J} \cdot J$$

in which: i_{N_J} is the N content of component J; S_i, X_i are components of ASM1; rS_i, rX_i are components of RWQM1. More details can be found in (Benedetti *et al.* 2003).

2.2 Site description and monitoring activity

The river Lambro lies in the north of Milano, Italy. The stretch under study has a length of 26km and a total drained area of approximately 300km^2. Lake Pusiano, which lies just upstream, gives it a steady flow regime. The most important pollution source in this stretch is the treatment plant of Merone, located at the beginning of the stretch. This treatment plant receives the wastewater of approximately 120.000PE. Prior to July 1998 it was constantly working at its maximum hydraulic capacity, with a daily overflow of dry weather wastewater (approximately 40% was regularly discharged untreated directly into the river).

All data used in the study were collected between March 1997 and May 1998, before the extension of the plant, in the context of the GREAT-ER Project (Schowanek *et al.* 2000). A nine-day study was performed at the Merone WWTP in July 1997 with the aim of evaluating plant efficiency. Twelve two-hourly composite samples of influent and effluent were collected over 24 hours on the first day, while 24 hour composite samples were collected on each of the remaining days. Samples were analysed for LAS, boron, total phosphorous, total nitrogen and suspended solids (Whelan et al., 1999). Concerning the river sampling, five automatic water quality samplers were placed along the study reach between November 1997 and May 1998, in order to collect 24 hours composite samples twice a month; one sampler was placed upstream and four downstream the plant, a sixth sampler at the inlet of the WWTP. The samples were analysed for LAS, boron and a series of standard water quality variables. In order to increase the understanding of the effect of the Merone plant on the water quality downstream, two extended measurement campaigns (February 1997 in dry weather conditions, and May 1998 in wet weather conditions) were performed with the objective to follow the diurnal wave of pollutant as it moved along the river stretch. Two-hourly samples were taken at six different stations using automatic samplers with staggered starting times. During both campaigns the flow was considered to be steady and the start times for the samplers were selected on the basis of river travel times estimated by a steady state hydraulic model (Gandolfi and Facchi 1998). Two gauging stations are placed within the study river stretch; for these sites flow rating curves (Q-h relationships) of good quality are available.

3 RESULTS AND DISCUSSION

3.1 The Merone WWTP modelling and calibration

Reactions in the AS units are described by the ASM1, with the parameters suggested in the report (Henze *et al.* 2000) as a starting point. An extra component was added to the model in order to describe the behaviour of LAS (common pollutant present in detergents) in the plant. LAS is known to degrade almost completely in AS treatment plants (Boeije *et al.* 1998) but only in aerobic conditions. A first order removal mechanism was assumed, combined with a switching function for oxygen which turned off degradation in anoxic conditions. Corresponding oxygen uptake and growth of heterotrophic biomass was also included, while the yield was taken the same as the yield during degradation of S_S in ASM1. The value for the degradation constant found by automatic calibration was 176d^{-1}, in good agreement with (Boeije *et al.* 1998) considering the different environmental conditions.

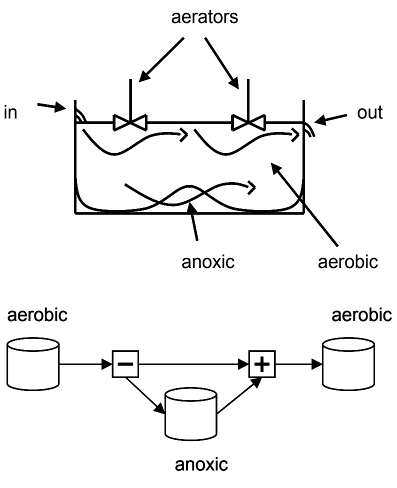

Figure 2: Hypothesis on water flow in aerated tanks (top), and modelling approach (bottom)

Available data were scarce and hence only an approximate calibration could be accomplished. Steady state calibration was performed on the average of the nine days, while dynamic calibration was performed on the data of day nine. The suspended solids concentration in the AS tanks was mainly influenced by the inert solids in the influent since these inerts accumulate in the system. Good results were obtained with a ratio of 40% of X_I and 60% of X_S in the inlet particulates.

Although both AS tanks are aerated, total nitrogen balances indicated simultaneous nitrification and denitrification in the plant. A macro-scale idea on how water flows in a tank with surface aerators is presented in figure 2 (top). As both aeration and in- and outflow occur at the top of the tank, some water may find a shortcut without entering the anoxic phase. At the bottom, water has a oxygen concentrations and flow velocity. This hypothesis was not confirmed by direct measurements, but it allows describing dead zones in a reasonable way (Alex *et al.* 2002). Therefore, two aerobic and one anoxic tank are used in the model, keeping the total volume equal to the existing volume (figure 2, bottom). Total nitrogen in the effluent was mainly influenced by the anoxic volume and the flow to the anoxic tank. Parameter adjustment yielded a volume of 10% and a flow of 5% to the anoxic tank. A sensitivity analysis showed that the anoxic tank volume did not have a large influence on the effluent LAS concentration, which is the main focus of this work. This could be explained by the fact that no degradation occurs under anoxic conditions, and the aerobic residence time was still sufficiently large to degrade most of the LAS.

3.2 The river Lambro modelling and calibration

Concerning the river Lambro, hydraulics was modelled by using a series of tanks with variable volume. This modelling approach requires the river to be divided into stretches, in which the end of a stretch usually coincides with river discontinuities or sites where information is available as input data or required as model output (Reda 1996). The river reach under study has been initially divided into five stretches, with the end of each stretch coinciding with sites in which water quality data were available. Data collected in dry weather were used for this calibration.

The pollution wave of boron coming from the bypass household wastewater has been used as a tracer to select the number of tanks necessary to model the hydraulic behaviour of the river Lambro. Boron is chemically inert and is a well established conservative tracer for use in environmental monitoring studies since it is not removed significantly in sewer systems, treatment plants or rivers (Matthijs *et al.* 1997). Results of simulations using different numbers of tanks showed that a good approximation of the peak shape at the end of the study river reach was given with 47 tanks (figure 3). The average length of tanks was found to be about 500m.

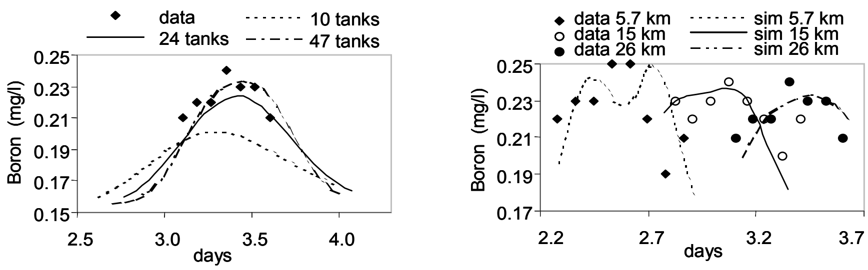

Figure 3: Effect of the number of tanks on dispersion after 26km (left), and longitudinal propagation of pollution wave with 47 tanks (right)

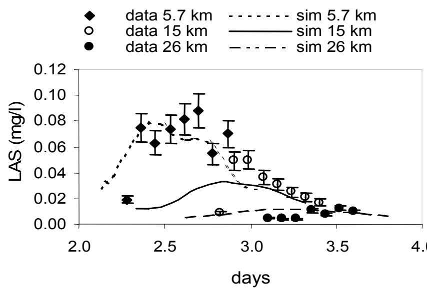

Figure 4: Simulated and measured LAS concentration in three river sections

Conversion processes are described by a simplified version of RWQM1, selecting relevant processes according to (Vanrolleghem *et al.* 2001). The same LAS removal mechanism as for ASM1 was added to the model. The LAS effluent concentration was mainly influenced by the first order degradation constant. The value found by "trial and error" calibration for this parameter was $0.085h^{-1}$, close to the values found for the Lambro by (Gandolfi and Facchi 1998) and (Whelan *et al.* 1999), and in the range of literature values(Boeije *et al.* 2000). Results are shown in figure 4.

3.3 Integrated simulations

The integrated model allows the evaluation of the effect of an upgrade at the plant (actually realized in July 1998) on LAS in the river. From figure 5 it is clear that the upgrade of the plant, consisting in a 100% increase of the primary settling volume and 50% increase of the aeration tank and secondary settling volumes, will have a positive effect on the river water quality of the Lambro during dry weather.

Even though no specific calibration data are available, the default values of RWQM1 allow to qualitatively judge the effect of some measures on the water quality. Although the model was not calibrated to predict ammonia or oxygen, the effect of the plant upgrade can clearly be noticed (results not shown). The amount of ammonia entering the river is much lower due to the larger fraction of water treated. Also, oxygen depletions were less deep, while nitrate concentrations were predicted to increase since only little denitrification takes place in the current treatment plant.

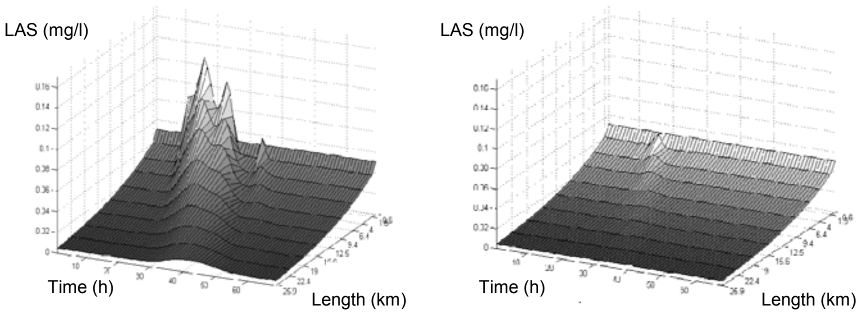

Figure 5: Predicted LAS concentrations with the old (left) and new (right) plant configuration

4 CONCLUSIONS

An integrated model of the treatment plant of Merone and the river Lambro was created with the aid of a interface between the ASM1 and RWQM1 models. Inherent features of this interface are its closed mass and elemental balances. The COD fractions of the ASM1 were split over the COD fractions of the RWQM1, while balance state variables were used to close elemental balances. Also, the different environmental conditions in the AS system and the river system were taken into account. A simple tanks-in-series model was able to adequately describe the dispersion in the river Lambro using Boron as a tracer. Also, LAS data could be modelled sufficiently well and the first order degradation constant found for LAS is within the range of degradation constants found in literature and close to the value found in other studies on the same river. As an example of application, the integrated model was used to simulate the effects of an upgrade of the undersized Merone plant. Simulation results show a clear improvement in river water quality with the upgraded plant, both for LAS and traditional pollutants.

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