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REQUIREMENTS FOR INTEGRATED WASTEWATER MODELS – DRIVEN BY RECEIVING WATER OBJECTIVES

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ABSTRACT

The design of efficient technical measures for the abatement of water pollution requires that wastewater discharge regulations are driven by receiving water objectives. However, such integrated water quality management is only possible when the impact to the aquatic ecosystem can be predicted quantitatively by means of integrated wastewater models. Typically, only a few types of wastewater discharge impacts are relevant for the state of the receiving water and, consequently, the structure of the model can be kept relatively simple when focusing on one of these impacts. The procedure of problem-oriented model selection is illustrated for three typical examples of acute water pollution, that is toxicity from un-ionized ammonia, hygienic hazard from pathogenic micro-organisms and oxygen depletion. © 1998 IAWQ. Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Integrated urban drainage management; modelling; receiving water impacts; water pollution; water quality .

INTRODUCTION

The ecological quality of a receiving water body is determined by numerous factors of which many are only poorly understood. However, it is quite obvious that it is not solely determined by the chemical water quality. Yet, receiving water regulations in many countries concentrate uniquely on wastewater discharges and do not take local ecological circumstances into account. As a consequence, technical measures to improve the ecological quality of receiving waters are most often uniformly applied end-of-pipe measures. Thereby, financial resources are not optimally used and, in the worst case, possibilities for more effective solutions in the future are at stake. In order to overcome the misconception "overflow reduction is receiving water protection" wastewater discharge regulations should be driven by receiving water objectives and problems (Lijklema *et al.*, 1993).

Wastewater discharge impacts on the receiving waters can be grouped into chemical, bio-chemical, physical, hygienic, aesthetic, hydraulic and hydrologic impacts. They can be further classified in terms of duration as acute, delayed or accumulating (Lijklema *et al.*, 1989). Typically, one or a few of these impacts dominate the ecological state of the receiving water: *This* is the impact to focus on, to describe it quantitatively, and to define measures to improve it. A procedure for such a receiving water oriented definition of objectives is outlined in Schilling *et al.*, (1997).

Once the key processes and their describing variables are found, the current state of the receiving water system must be characterised and the effects of various engineering measures estimated. Since monitoring is usually too cumbersome and expensive, models must be used that describe the numerous sources of wastewater discharges, the receiving water processes and their interactions. Today we already have a number of integrated models available for the description of the dynamics in the total system. However, those integrated models usually are a combination of models that have been developed with a different objective in mind, i.e. simulating the behaviour of a specific subsystem in detail. The combination of these models is often not appropriate, as the amount of information given is not required for the task in mind. Pragmatism is required to avoid unnecessary complexity IN these models. In this paper we discuss both the background and the application of integrated wastewater models for some typical purposes.

SYSTEM DESCRIPTION

The system considered includes the sewer system, the wastewater treatment plant (WWTP) and the receiving water. The sewer network was originally constructed to transport the wastewater - that includes sewage, storm water and clean water inflow - as completely and as fast as possible out of the settlement area in order to guarantee hygiene and flood protection. The WWTP is the end-of-pipe solution to protect the receiving water from the effects of this efficient transport. The goal of the system is traditionally determined by emission standards that refer to the performance of the sub-systems. Thus, common strategies aim at optimising the individual sub-systems.

Today the strategy has changed. The present approach is to transport as little combined water as possible in the sewer and make use of the retention capacity (i.e. transport the water as slow as possible), without violating the conditions of hygiene and flood protection. Further, the impact on the receiving water is regarded as decisive to assess the system's performance rather than a simple sub-system criterion such as to allow a certain number of combined sewer overflows (CSO) per year. The dynamic loads of compounds from both CSOs and WWTP are significant rather than volumetric balances. Therefore, the diurnal variation of the sewage and the compounds fluxes (e.g. nitrogen, Krebs *et al.*, 1996) or the self-purification processes in the receiving water (e.g. dissolved oxygen, Rauch and Harremoës, 1996 and 1997) become more important than e.g. the overflow rate. For the modelling of the integrated system, the receiving water must thus be considered as an integral part of the system. Depending on the variables to follow and on the characteristics of the receiving water, the system boundaries and the processes to be modelled vary within a wide range.

PROBLEM OF MODELING THE INTEGRATED SYSTEM

Background

Today, models are available that can reasonably simulate the behaviour of the individual sub-systems, although they may be fairly complex and their parameters hardly identifiable. The uncertainty of the model predictions not only originates from overparametrisation, but also from the stochastic nature of some of the processes. For instance, rainfall and its unpredictable distribution in space and time is in many cases the most important input to the rainfall-runoff simulation, and is the driving force whether a CSO event takes place or not. The base flow in the receiving water is decisive for its self-purification capacity and oxygen balance, and is influenced by stochastic factors among which the duration of the preceding dry-weather period is presumably the most important one. In WWTP's equipment failures, toxicity events and inherent biological variation produce unpredictable behaviour as well.

Incompatibility of subsystem models

Integrating over the three sub-systems is more complex since the decisive processes to be modelled in the individual systems are different. Also, the variables considered important for the different sub-units of an urban catchment reflect the history of the development of these models and of the goals that were set in sanitary engineering. Indeed, mathematical models are largely dependent on the purpose they are meant for. For instance, a lot of attention was paid in the past to modeling the sewer's hydraulics in great detail (as flood prevention was one of the main purposes of the sewer system), while the quality of the conveyed sewage was hardly considered. Biological processes in the sewer system may not be considered important when the CSO load is to be determined, but they can be significant with respect to a reliable prediction of the input load to the WWTP. In recent years this flaw has been recognised and research projects have been initiated to build models for quality predictions. Similar changes in focus have resulted in considerable shifts in model descriptions over the past few years. For integrated simulation, existing models of sub-systems can be used, but translating the state variables at the interfaces turns out to be a major problem.

As a result considerable differences in modelling approaches result in compatibility problems when one wants to create an integrated model for overall performance assessment. To illustrate some of the main "connection" problems, Table 1 gives an overview of the most commonly used state variables in the models of the different subsystems.

Table 1. Comparison of state variables used in models of the different subsystems of an urban catchment

Sewer System		Wastewater Treatment Plant		River	
Flow Rate		Flow Rate		Flow Rate	
Total Suspended Solids		Total Suspended Solids		Total Suspended Solids	
BOD	-> particulate -> soluble	COD	inert soluble (S_I) soluble readily biodegradable (S_S) inert particulate (X_I) slowly biodegradable (X_S) heterotrophic biomass (X_{BH}) autotrophic biomass (X_{BA})	BOD	slowly biodegradable readily biodegradable sediment oxygen demand
Total (Kjeldahl) Nitrogen		N	ammonium (S_{NH}) nitrate (S_{NO}) soluble biodegradable (S_{ND}) inert soluble (S_{NI}) slowly biodegradable (X_{ND})	N	ammonium nitrite nitrate Kjeldahl
		Dissolved oxygen		Dissolved oxygen	
Total Phosphate				Phosphate	inorganic organic
Fecal coliforms				Fecal coliforms	
				Chlorophyl a	
				pH	

From Table 1 it is quite obvious that different levels of detail are used in the different models, as illustrated by the fractionation of organic matter and nitrogen compounds in the different subsystem models. Moreover, different descriptors are used occasionally for the same quality aspects, e.g. BOD as a measure of organic pollution in sewer and river models and COD in WWTP models. Finally, some state variables are not felt to be significant at all in certain subsystems, such as heterotrophic biomass in sewer and river models. All these differences clearly reflect the different interests of the people who developed the models. As today this interest has shifted to combined use of these models, clear compatibility issues are raised. These are typically solved either by assuming values for variables that were not used for modelling in the upstream subsystem, or by creating ad hoc (based on experimental evidence whenever possible) conversion factors (e.g. Vanrolleghem *et al.*, 1996). Recently, some work has been initiated to create compatible models in which a common set of state variables is suggested (Fronteau *et al.*, 1997; Maryns & Bauwens, 1997). Also, a task group has been set up within IAWQ in order to build a modelling suite for receiving waters that is compatible with the de facto standard IAWQ Activated Sludge Models (Somlyody *et al.*, in press).

PROBLEM ORIENTATED MODEL SELECTION

Background

In integrated modelling the level of complexity of the subsystem models should be consistent. It does not make sense to apply very detailed models to estimate the loads from a sewer system and treatment plant, if subsequently a highly aggregated receiving water model is used. In turn, the use of a complex river water quality model is not required if loading rates are predicted by simple WWTP or urban runoff quality models. As holds for any modelling exercise, the level of complexity should be based on the goals of the study. Here, the starting point should be the receiving water impact to be predicted. Most important state variables and controlling processes in the receiving water should be identified and, subsequently, the required inputs at the interfaces with the other subsystems can be selected. From there the appropriate complexity of the model for the other two subsystems can be selected. This should be done in such a way that these models provide sufficiently accurate estimates of the input variables for the receiving water model. In the following this procedure is illustrated for three types of acute receiving water impacts (Table 2).

Table 2. Minimal structure of integrated models for assessment of specific acute impacts

Water Quality problem		Sewer	WWTP	River
Toxic impact (NH_3)	Processes	transport + mixing, runoff	transport + mixing, nitrification	mixing
	State Variables	N_{tot} (= NH_4 in worst case)	NH_4, X_{BA} (autotroph Bacteria)	NH_4, pH (observed)
Hygenic (FC)	Processes	transport + mixing, runoff	.	transport + mixing, decay
	State Variables	FC	FC_{eff} = constant	FC
Oxygen depletion	Processes	transport + mixing, runoff settling in storage tanks	transport + mixing, conversion according ASM1, sedimentation	transport + mixing, conversion, reaeration, Sediment oxygen demand
	State Variables	COD/BOD	COD fractions	BOD, fractions; DO

Ammonia

Ammonia is, depending on pH and temperature, in chemical equilibrium with unionized ammonia which is toxic to fish. Therefore, the discharge of ammonia from the urban wastewater system is often decisive when the oxygen concentration in the river is not a problem. An example is given here which is computed with a simplified model developed to determine the concentration of ammonia in the receiving water caused by CSO and WWTP effluent.

The test system is a village near Zurich, Switzerland, which is described in detail in Holzer and Krebs (in press). The model comprises the overflow structure, a combined sewage retention tank (or alternatively a sewage retention tank to store the sewage of a separate sewer system before it enters the combined sewer system) that is located just before the WWTP, the WWTP and the local river section. It was set up on the basis of AQUASIM (Reichert, 1994) which is an open-structured software tool. Unlike in Holzer and Krebs, the model includes only the minimum number of processes necessary to focus on ammonia. The runoff process in the settlement area and the sewer system was simulated individually with the software MOUSE (DHI, 1996) and used subsequently as an input to the model introduced here. The input of ammonia was estimated from typical diurnal variations (Siegrist and Boller, 1988) of the sewage and from typical values of background storm water concentrations (Mottier and Eugster, 1996).

The hydrograph in the receiving water was taken from a continuously operated measuring station, situated 2 km upstream of the CSO structure and the WWTP effluent. The local river section in the model was simplified as 2 completely stirred tank reactors (CSTRs) with the hydrograph measurement used as input. The processes in the river downstream of the WWTP effluent are of no importance for this problem as the maximum concentration of ammonia is found at the location of the discharges. Further downstream, nitrification reduces the ammonia concentrations (Jancarkova and Gujer, 1996). Note that by assuming immediate mixing in the river, the local concentrations are underestimated.

In the WWTP only the processes concerning the nitrogen balance are considered. The model set-up - including a primary clarifier, a nitrifying activated sludge process and a secondary clarifier consisting of a supernatant part and a sludge bed where denitrification was modeled - was the same as described in Holzer and Krebs (in press).

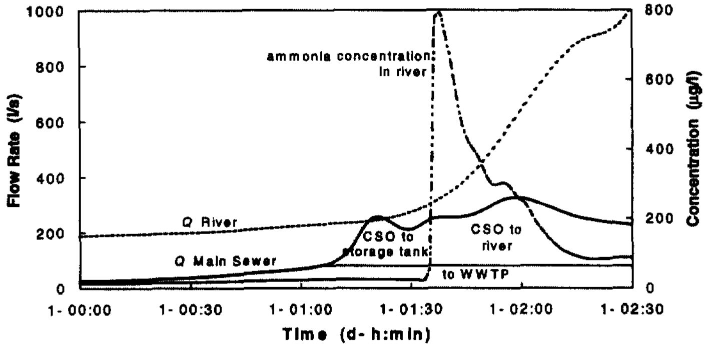

Figure 1. Example result of a simulation run to determine the ammonia concentration in the receiving water.

An example result is shown in Fig. 1 (see Holzer and Krebs, in press, for more examples). The event was relatively short and of medium rain intensity. Even though, in the critical phase shown, the overflow to the river is in the same order of magnitude as the flow rate in the river, the concentration does not become critical, as the CSO event occurs during night hours when the sewage concentrations are small. For the same reason, the WWTP is not overloaded and does not significantly contribute to the total impact in this case.

Faecal coliform

In order to evaluate the potential danger of the transmission of waterborne diseases, indicator bacterial groups are used to reflect the potential presence of pathogenic microorganisms. Faecal coliform bacteria (FC) have been used frequently for that purpose and, hence, there is satisfactory data on the contamination of the receiving water caused by raw sewage, combined sewer overflow and by the effluent of treatment plants (Table 3). A high content of FC in the receiving water indicates the acute pollution of the river with respect to human recreational use. The following example investigates the potential hygienic hazard of a bathing place in a river induced by an upstream wastewater system.

Table 3. Typical mean values for the number of fecal coliforms (cfu) per 100 ml (from Metcalf and Eddy, 1991)

	Raw sewage	Stormwater	WWTP-effluent
Fecal Coliforms [cfu/100 ml]	10^7	10^3	10^5

The hypothetical test case resembles, in some features, the situation found at the river Isar, Bavaria (Kilian and Lenhart, 1995): An urban catchment (impervious area = 400 ha; 80 000 PE; 150 l/PE/d) discharges into a river (baseflow = 17 m^3/s, velocity = 1 m/s) with a bathing place located 23 km downstream. The maximum hydraulic capacity of the treatment plant is assumed as 0.6 m^3/s and the size of the detention basin as 8000 m^3. In order to predict the FC concentration at the bathing place as a result of a storm event the simplest possible models have been used for simulation of the processes in the three subsystems. Rain runoff from the urban settlement is described by means of a simple regression model, i.e. the unit hydrograph method. The quality of the combined sewage is calculated by mixing of raw sewage and stormwater with the constant concentrations given in Table 3. The conversion processes in the wastewater treatment plant are conveniently neglected and a constant FC concentration in the effluent is assumed (note that the efficiency of the WWTP is reduced during periods of high hydraulic loading). The transport and mixing phenomena in the river is described here by using the reactor principle (Rauch *et al.*, in press).

Disappearance of FC in the receiving water is a complex process influenced by the metabolism of the bacteria, environmental conditions (sunlight is most important) and sedimentation. According to common practice (reviewed by Bowie *et al.*, 1985) the total phenomena is computed here by means of first order kinetics (disappearance rate = 1 d^{-1}). This combination of models follows stringently the minimal structure proposed in Table 2 for the assessment of hygienic impacts.

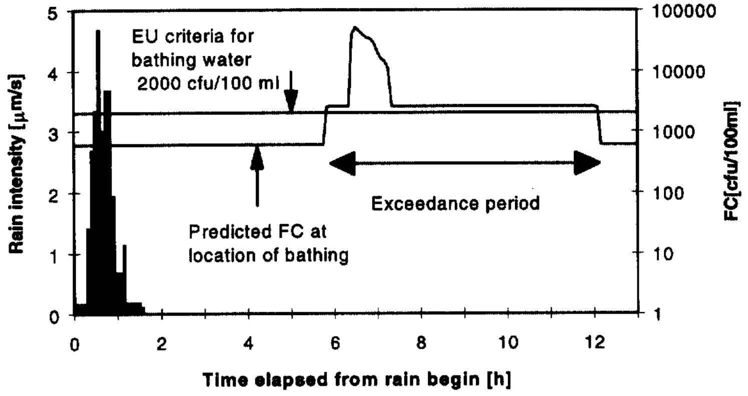

Figure 2. Predicted impact of FC at the bathing place as a result of a rain event (8.6 mm).

Figure 2 reveals that even a short rain event of lower intensity is likely to cause acute pollution at the location of the bathing place (violation of EU-criteria). The reason is that FC concentration in the stormwater is negligible compared to the concentration in raw sewage. Hence, significant pollution occurs mainly when low rain intensity causes overflow while still maintaining a high sewage/stormwater ratio and a relatively small base flow in the river that hardly reacts to the rain event.

Dissolved oxygen (DO)

Oxygen depletion in rivers has been a major concern and has been modelled ever since the ground-breaking work of Streeter and Phelps (1925). Fish cannot stand oxygen depletion below critical levels for longer periods of time and therefore the lethal effect is usually assessed statistically (e.g. Harremoës and Rauch, 1996). Below, a simulation study is reported in which the effects of operating scenarios are studied in a virtual urban catchment of 300.000 PE. Aim of the study was to evaluate a methodology in which long-term simulations of an integrated model of the sewer system, activated sludge WWTP and river stretch are performed. The impact of a whole range of rain events is statistically analysed in terms of concentration-duration-frequency curves with respect to DO in the river.

In this case study only the effect of the sewage discharge on dissolved oxygen levels in the receiving water was assumed as being important. Moreover, the receiving water in mind is characterised by complete absence of nitrifying and photosynthetic activity. Hence, only biodegradation of organic matter had to be modelled in the receiving body (see Table 2). Consequently, the sewer and WWTP models could be simplified, as they only had to provide the necessary inputs to the mass balances in the river model. In the study, the KOSIM hydrological sewer model was used to describe the routing of organic matter expressed as COD, taking into account the dry weather discharge and run-off. Neither conversions nor sedimentation of compounds were assumed in the network, while settling of organic matter in the installed basins was described. The existing catchment is characterised by a high annual number of CSOs at the 5 overflow structures (CSO scenario). An alternative scenario was therefore evaluated in which a considerable volume of stormwater retention basins was installed in the sewer system (BAS scenario). The WWTP model was a reduced IAWQ Activated Sludge Model no. 1 (Henze *et al.*, 1987) in which only the biological COD-removal was retained. As settleable solids were considered in the receiving water for delayed oxygen demand, care was taken to adequately describe the behaviour of primary and secondary settlers in the WWTP. Typical operational schemes were also evaluated in the study. Details are found in Vanrolleghem *et al.* (1996).

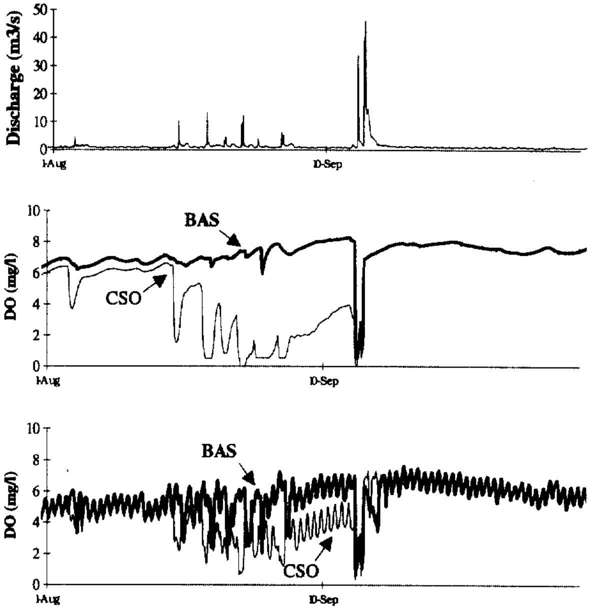

Figure 3. Simulated response of a catchment on urban discharges under rain events of different magnitude. River flow (top), oxygen levels upstream the outlet of the WWTP induced by the CSO and BAS sewer options (centre) and oxygen levels downstream of the WWTP for the same options (bottom).

Figure 3 shows typical simulation results with this ultimately aggregated model from which the concentration-duration-frequency statistics with respect to DO in the receiving water can be deduced. Relatively minor storm events typically observed in late summer in this catchment result in considerable oxygen depletion during the low flow regime of the receiving water. Introduction of retention basins in the sewer network can obviously postpone the impact of the event to the downstream discharge point of the WWTP. Even though the WWTP suffers from the increased load when the stormwater basins are emptied, the net effect is still positive in this modelling exercise.

CONCLUSIONS

Technical measures for the abatement of water pollution from the urban drainage system are traditionally based on uniformly applied emission restrictions. Experience revealed that this approach is no longer appropriate and that decisions have to be based on an evaluation of the receiving water quality. Models for the description of the dynamic behaviour of the sewer system, the WWTP and the river are available and also frequently applied, but the combination of those models for the assessment of water pollution gives rise to a model complexity far beyond of what is needed. Simplifications are possible since only a few types of wastewater discharge impacts typically affect the ecological state of the receiving water. Consequently, the integrated wastewater model has to focus only on (one of) these impacts and all additional information is to be regarded as superfluous. Therefore, from an integrated wastewater management perspective, existing models of the subsystems are often too complex as their development was driven by the requirement of detailed understanding of the dynamics within that particular subsystem.

In order to avoid compatibility problems when trying to link models it is crucial to (i) determine the relevant receiving water impact, (ii) identify for all subsystems the minimum set of state variables and processes that are necessary to appropriately describe the impact, and (iii) specify the inputs/transformations at the model interfaces. This procedure was successfully applied for three typical examples of acute water pollution.

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