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SETTING UP MEASURING CAMPAIGNS FOR INTEGRATED WASTEWATER MODELLING

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ABSTRACT

The steps of calibration/confirmation of models in a suggested 11-step procedure for analysis, planning and implementation of integrated urban wastewater management systems is focused upon in this paper. Based on ample experience obtained in comprehensive investigations throughout Europe recommendations have been formulated for design of measuring campaigns. The inclusion of iteration in the overall planning of measuring campaigns is advised and the use of preliminary sensitivity analysis is shown to allow maximisation of information retrieval from experimental efforts. Case studies covering problems related to suspended solids, specific contaminants, hygienic hazards and total pollutant loss illustrate the recommendations presented. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Experimental design; mathematical modelling; urban water management; wastewater treatment.

INTRODUCTION

This paper is the third in a series that deals with modelling for urban wastewater management. In the first paper (Schilling *et al.*, 1997) operational wastewater management goals (pollution discharge protection) were confronted with the receiving water objectives. It was clearly indicated that different uses of receiving waters lead to different operational management goals. A procedure was outlined to find the critical indicator(s) on which the design and operation of the wastewater infrastructure should focus upon from a receiving water oriented objective.

In the second paper (Rauch *et al.*, 1998a) attention was focused on the models that are typically used to tackle such management problems. From the conclusions of the first paper, the starting point was that only a few types of wastewater discharge impacts dominate the state of the receiving water and that, consequently, the structure of the model can be kept relatively simple when focusing on one of these impacts. The proposed procedure of problem-oriented model selection was illustrated for three typical examples of acute water pollution, i.e. toxicity from unionized ammonia, hygienic hazard from pathogens and oxygen depletion.

The solution of urban wastewater management problems typically follows a stepwise procedure as depicted in Table 1. The first seven steps in this procedure were discussed at length in the first two papers. The more concrete steps of an urban wastewater management study are now to be tackled: calibration and confirmation (often referred to as validation, step 8) of the selected model(s) are necessary steps to obtain a reasonable description for quantitative analysis of different alternative solutions of the problem at hand (step 9). More specifically, attention will be focused in this paper on the measuring campaigns that are required to generate the necessary, highly informative, data for these steps. The mathematical techniques underlying parameter estimation and model structure identification on the basis of these data will not be covered here, but can be found elsewhere (e.g. Vanrolleghem and Dochain, 1998).

Table 1. Procedure to analyse, plan and implement integrated wastewater management systems

1. Define receiving water uses and ecological state
   (from historical experience and /or as the result of a kick-off event)
2. Evaluate the degree of satisfaction (political level):
   2.1 Uses satisfied ?
   2.2 Ecological quality sufficient ?
   2.3 Conflicts between uses and ecological quality?
3. Define objectives (scientific, specified with figures)
   3.1 Satisfy uses
   3.2 Improve ecological state
   3.3 Resolve conflicts
4. Identify problems (according to Schilling *et al.*, 1997)
   4.1 Classify receiving water according to available system / process data ("prior knowledge")
   4.2 Identify crucial / important indicators
5. Generate list of potential solutions
   (structural vs. operational, internal vs. external to the system)
6. Identify minimum model structure (according to Rauch *et al.*, 1998a)
   6.1 Identify indicator variables
   6.2 Backtrack relevant processes influencing the indicator variables
   6.3 List relevant input-, state-, and output-variables
7. Select candidate model(s), i.e. the set of equations
8. Calibrate / confirm the model using data collected in well-designed **measuring campaigns**. If not possible go to 7 or to 4.
9. Evaluate alternative solutions with the model(s)
10. Decision making
11. Implementation, post-implementation audit.

RECOMMENDATIONS FOR MEASURING CAMPAIGNS

Measuring campaigns to support identification of integrated urban wastewater models may become huge. Indeed, measuring periods for a few years at measurement sampling intervals of tens of seconds are necessary when one tries to cover the range of time constants present in the system (tens of seconds for oxygen and flow dynamics in treatment plant and sewer, respectively, and up to months for population dynamics in treatment plants and rivers). In addition, sewer networks and rivers are distributed parameter systems requiring measurements at multiple locations. Obviously, such campaigns can become very expensive and are probably only feasible within research programmes. From such programmes, recommendations should be drawn for measuring campaigns oriented to (support models to) solve particular receiving water problems.

Experience gained in a considerable number of studies related to integrated wastewater modelling (Table 2) is summarised in the following recommendations for setting up measuring campaigns.

Table 2. List of integrated urban wastewater management studies in which important integrated measuring campaigns were conducted ("X" indicates monitored systems)

Location/ River	Objective	Analyses included: Wastewater production	Sewer system	Wastewater treatment	Receiving water	Ref.[&]
Trondheim (N)	Min. tot. pollution	X	X	X		2 P; 1 TR
Lambro (I)	Risk assessment			X	X	1 TR
Bordeaux (F)	Research	X	X		X	2 A
Boran-s-Oise (F)	Research	X	X	X		2 P
Loenen (NL)	Research		X		X	n P
Vecht (NL)	Scenario analysis			X	X	n P
Hildesheim (D)	Research	X	X	X	X	2 P
Innsbruck (A)	Effect infiltration	X	X		X	2 P
Glatt (CH)	Research		X	X	X	1 TR; 2 P
Tielt (B)	Min. tot. pollution	X	X	X	X	1 P
Aalborg (DK)	Real-time control		X	X	X	n P
Avedore (DK)	WWTP operation	X	X	X		1 P
Rhine-Rhône (F)	Channel design	X			X	n P
Paris (F)	Research	X	X		X	n P

[&] References available: A: abstract, P: paper, TR: technical report.

Trondheim:	Milina *et al.* (1999); Schilling *et al.* (1998)	Innsbruck:	Rauch *et al.* (1998b,c)
Lambro:	Whelan *et al.* (1997)	Glatt:	Krejci *et al.* (1998)
Bordeaux:	Jacopin *et al.* (1999)	Tielt:	Heip *et al.* (1997)
Boran-s-Oise:	Bertrand-Krajewski *et al.* (1995,1997)	Aalborg:	Carstensen *et al.* (1996)
Hildesheim:	Lammersen (1997)	Avedore:	Carstensen *et al.* (1998)
Loenen:	Lijklema *et al.* (1987)	Rhine-Rhône:	Tassin and Lucas (1993)
Vecht:	Aalderink *et al.* (1996)	Paris:	Mouchel and Simon (1993)

The main advice for setting up a good experimental plan is to invest considerable time in carefully assessing the following aspects of an experimental design, i.e. (Vanrolleghem and Dochain, 1998):

- what variables should be measured?
- what is the required accuracy of the measurements?
- over what period has the experiment to last?
- at what frequency are the different variables to be measured?
- where are the measurements to be made?

A second important recommendation is to include from the start the possibility for iteration in the exercise. Indeed, it is felt that starting with a small preliminary measuring campaign to get an initial understanding of the system can be very valuable to direct the full-size measuring campaign that must follow. Too many large measuring campaigns are set up, executed and afterwards found to have resulted in plenty of rather uninformative data.

Some characteristics of the system and/or the problem at hand may result in the choice for one or the other measuring set-up. For instance, if longer periods of continuous measurements at high measurmg frequencies are required, the use of automatic measuring stations (as the one illustrated in Figure 1) may become cost effective. One should note, however, that maintenance costs for such measuring stations may become substantial, and should be budgeted at about one third of the investment cost of the installed equipment per year (Lammersen, 1997). Data drowning may become an issue and data management should, therefore, receive adequate attention.

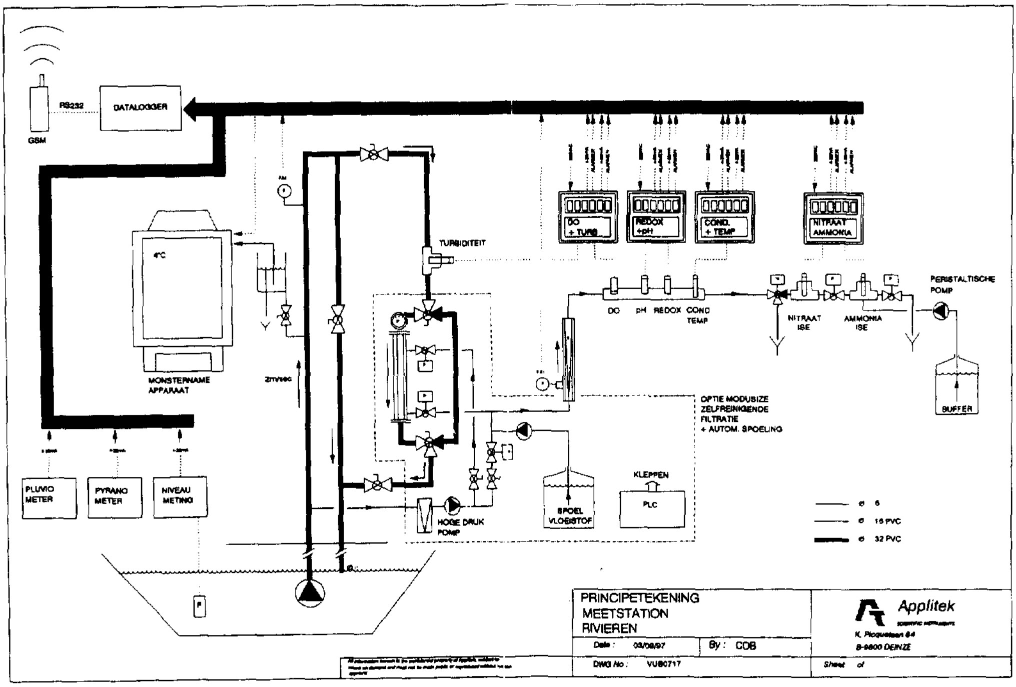

Figure 1. Scheme of an advanced measuring station for continuous on-line surface water monitoring of Ammonia, ChlA fluorescence Conductivity, Dissolved Oxygen, Flow rate, Light intensity, Nitrate, pH, Rainfall intensity, Redox, Temperature, Turbidity and the possibility to collect refrigerated samples.

Another example of a system feature that may determine the measuring campaign is the presence or absence of significant dispersion in a river. The importance of dispersion can rather easily be evaluated using simple measurements or empirical relationships such as Dobbins' Criterion (Dobbins, 1964):

$$2kD/V^2 < 10^{-2}$$

where k is the largest rate constant (T^{-1}), D is the dispersion coefficient (L^2T^{-1}) and v is the flow velocity (LT^{-1}). When it can be assumed that dispersion is negligible, one can restrain the experimental programme to one in which a plug of liquid is followed as it propagates downstream, rather than to invest in continuous monitoring of river characteristics at multiple locations (Gandolfi *et al.*, 1996). Similarly, stratification in lakes, or horizontal mixing in rivers can be assessed and can support the decision to go for a more or less complicated experimental design. Basically, such multidimensional measuring problems (time as one independent variable and, possibly, one or more spatial variables) can be reduced substantially in size if one dimension can be omitted as being irrelevant, e.g. because mixing is sufficient.

A prior run of the model that is to be calibrated in setting up the measuring campaign can be very useful in getting a feeling for the necessary sampling frequencies and optimal locations. Although optimal experimental design theory, built around the Fisher Information Matrix, exists (see e.g. Vanrolleghem and Dochain, 1998), its application to huge systems as an urban wastewater system, seems impractical at this stage. However, the underlying principles can be used to direct measuring campaign design. Using the model, the sensitivity of a variable on a parameter, i.e. to what extent a model prediction depends on the parameter value, can be predicted. Where the sensitivity is maximal, most information is available on the parameter and a measurement of that variable at the time or place of maximal sensitivity is very cost effective. The illustration of this approach in Figures 2 and 3 is related to the calibration of a treatment plant model used in an integrated setting (Vanrolleghem *et al.*, 1996). The figures show the sensitivity of the effluent suspended solids with respect to the settling model parameter r_h in the Takacs *et al.* (1991) model for the final clarifier. It can be observed that the best measurement instances to assess this parameter are those when the treatment plant is subjected to high flow rates. Dry weather conditions are very uninformative for r_h.

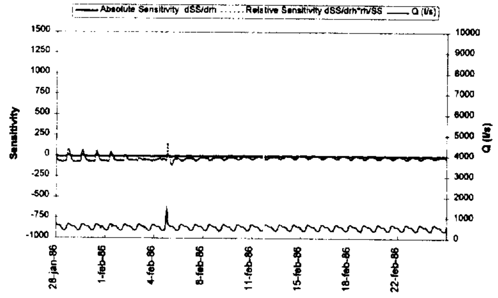

Figure 2. Sensitivity of the effluent suspended solids on settling parameter r_h during wet weather flow conditions prevailing in February 1986.

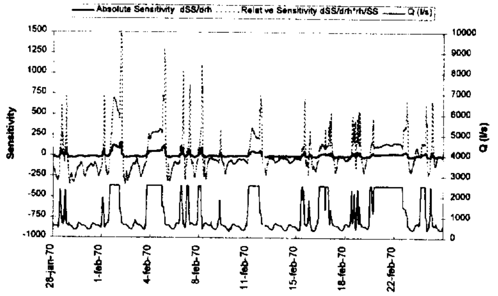

Figure 3. Sensitivity of the effluent suspended solids on settling parameter r_h during dry weather flow conditions prevailing in February 1970.

It is important to note that a sensitivity evaluation typically has to be performed with a not-yet-calibrated model in which best guesses for the parameters are included. Evidently, when a preliminary experiment is performed as suggested above, one can improve the parameter values included in the model and in this way increase the reliability with which the follow-up full-size measuring campaign can be planned. This again stresses the importance of an iterative procedure for model calibration in which multiple runs of measuring campaigns and model calibrations are foreseen.

A final recommendation relates to the use of simple mass balances. They can support the decision whether one or the other input is relevant (e.g. diffuse inputs vs. combined sewer overflows) and may also support evaluation of the quality of the measurement data. It may be very worthwhile to design a measuring set up that allows one to apply mass balances with the available data, e.g. by including sampling locations at all inputs of a stretch and at its output.

MEASURED VARIABLES

In Table 3 an overview is given of variables that can be measured reliably in the different subsystems with automatic measuring stations. In the wastewater production subsystem no routine or online measurements are available. Assessment of sewage volumes, pollutant loads and fluxes is largely carried out by calculating products of population equivalents and specific production qualities, i.e.

"N-concentration in sewage " = "PE" x "N-production per PE" / "water consumption per PE"

The time aspect is introduced by including typical time variations as assessed by specific studies (Butler *et al.*, 1995). Note that special attention should be given to the impact of residential vs. commuter areas to quantify the number of population equivalents (Heip *et al.*, 1997). In-sewer on-line measurements mainly include

- water level (by pressure transducer, ultrasound, bubbler)
- flow gauges (flumes, full pipe-electromagnetic, ultrasound)

and occasionally turbidity (correlates with SS), UV-absorption (correlates with COD) and conductivity (indicates dilution with runoff and correlates with NH_4). Solids measurements are not routinely applied.

Table 3. On-line measurements that can be/are carried out in measuring campaigns

Wastewater production	Sewer system	Wastewater treatment	Receiving water
Population Equivalents (PE)	Water level	Flow rate	Water level
Water consumption per PE	Flow gauges	Oxygen	Flow rate
COD production per PE	Turbidity (≈SS)	Turbidity (≈SS)	Oxygen
N production per PE	UV-absorption (≈COD)	NH_4^+	Turbidity (≈SS)
	Conductivity (≈NH_4^+)	NO_3^-	NH_4^+
Rainfall runoff		Phosphates	NO_3^-
Snowmelt runoff	Oxygen		Wind speed
Infiltration/exfiltration flow	Temperature	Temperature	Temperature (liquid/air)
		pH	pH
		Redox	Conductivity
		Sludge blanket	Chlorophyl-A
		Settleability	Light Intensity
		Toxicity	Toxicity

However, experience indicates that in terms of mass balance during a rainfall event, input and output are small compared to the total sediment deposits present in the sewer system. In a French study (Mouchel, personal communication) 60% of the total overflow-/outflow-load during a storm originated from the sediments, but only as little as 1 mm deposit was washed off. It was shown that only 1% of the moveable sewer sediment was washed out in a medium storm, i.e. even when the ratios are not so distinct as in the French study, sediment can be considered to be an unlimited resource when sediment is present in the sewer.

From this, the following procedure can be suggested:

- identify sewer reaches with/without sediments from sewer maintenance crews;
- if without deposits: sedimentation/resuspension can be neglected;
- if with deposits: deposits are considered an infinite resource, and resuspension should be modelled.

In the wastewater treatment subsystem considerable investments in on-line instrumentation are increasingly made (Table 3). In terms of important quantities for the treatment plant models, the lack of sensors for active biomass and the different COD-fractions is particularly felt.

There are many similarities between the sewer and receiving water subsystem with respect to on-line measurements. A major difference, however, is the possible gradients in depth and width that are important in larger receiving waters. Hence, the relative location of sampling points is very important, especially since forced mixing is impossible in rivers. Flow (i.e. the total flow balance) is the most important variable. Here, temperature and conductivity might be used to determine groundwater inflow or outflow. As in the treatment system, measurements that are particularly important for modelling purposes, but are not available (yet) relate to biomass activities (in the water and sediment phases).

Although the above indicates that considerable information can be gathered from on-line instruments, still sampling and lab analysis form the backbone of most measuring campaigns. Attention should especially be given to the problems of adequate sampling strategies, particularly in sewers and receiving waters where pronounced sediment build-up may occur.

CASE STUDY I: SUSPENDED SOLIDS AND SPECIFIC CONTAMINANTS

Some 40 collaborators of the Swiss Federal Institute for Environmental Science and Technology (EAWAG) were involved in the Glatt case-study (Gujer *et al.*, 1982; Krejci *et al.*, 1998). The measurement campaign concentrated on the dynamics during a storm event. The water and various compounds were followed from the source to the sink to gain insight into the processes related to rain events in a watershed. Two aspects are pointed out in this paper: (i) the significance of the release of suspended solids in the WWTP effluent during dry-weather periods for the oxygen demand in the receiving water during rain events and (ii) the mechanism that makes contaminants appear in the groundwater aquifer shortly after they are present in the river. These aspects demonstrate that a preliminary experimental study may cause an extension of the system and processes when the model should be able to predict certain effects.

The river Glatt watershed has an area of about 260 km^2 and is densely urbanised (900 inhabitants/km^2). The river is relatively weak as receiving water with an average flow rate of 3.3 to 8.5 m^3/s. The rain event was monitored at a few important spots: (i) at the CSO of a representative drainage catchment; (ii) at the WWTP that is the dominating pollutant source along the receiving water; (iii) before the monitored CSO and WWTP; (iv) at 5 km (Rumlang); (v) 15 km (Glattfelden) downstream of the WWTP; and (vi) at a groundwater sampling station near the Glattfelden observation site. Rain intensity measurements were available from several rain gauges which showed a strong spatial variation for the observed event.

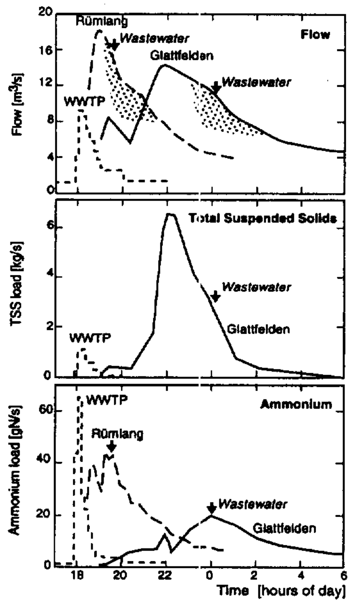

Figure 4. Flow rate and pollutant loads in the river Glatt and in the effluent of the WWTP Zürich Glatt.

Figure 4 shows the variation of the flow rate and the loads of suspended solids (TSS) and ammonium at different locations along the river Glatt. The TSS peak load coincides with the peak flow rate, indicating that the solids load occurs due to resuspension from the river bed rather than inputs during the storm event. A mass balance of particulate organic carbon (POC) revealed that at least 2/3 of the accumulated POC load detected in the downstream river measuring-station originated from resuspension of solids that have been discharged via the WWTP effluent and sedimented in the river during the dry-weather period previous to the event. Since the resuspended sediments may cause a serious oxygen demand, the interaction between dry- and wet-weather conditions can be a decisive load factor if dissolved oxygen is a concern in the receiving water.

The ammonia peak arrives significantly later at the downstream measuring station of Glattfelden. It originates from the CSO and the WWTP, and is thus a tracer of the flow velocity. Due to the fact that the wave celerity is higher than the flow velocity, the flow-rate peak occurs earlier (see e.g. Krebs *et al.*, 1998). The timing of flow, dissolved compounds and suspended solids is another indicator that the TSS concentration is produced by erosion of river sediments.

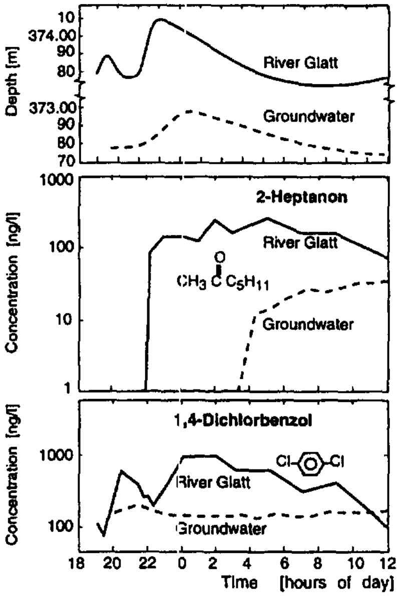

Figure 5. Variation of water depth and pollutant concentrations in the river Glatt and the nearby groundwater (2.5 m from river bank).

Intense turbulence and erosion of the river bed and risen water levels during peak discharge lead to a higher permeability of the river bed and to increased pressure gradients between the river and the groundwater, respectively. Therefore, infiltration of surface water to the groundwater aquifer is enhanced and so are dissolved chemical pollutants present in the river during storm runoff. The fate of organic contaminants during infiltration is influenced by processes such as dispersion, adsorption, biological transformation and degradation. Figure 5 illustrates the behaviour of two organic trace contaminants. 2-Heptanon, which has not been observed before the event, either in the river or in the aquifer, was detected in the groundwater (2.5 m from the river bed) only 5.5 hours after its appearance in the river. In contrast, 1,4-Dichlorobenzene is adsorbed and thus the groundwater concentration hardly reacts to the event.

CASE STUDY II: HYGIENIC HAZARD

This case study aims at the evaluation of the potential hygienic hazard of a bathing place at a river, induced by an upstream drainage system. The integrated model (Rauch *et al.*, 1998a) is using only one single state variable for expressing water quality, that is fecal coliform bacteria (FC). The measurements for calibration and confirmation of the model are therefore concerned with (1) the flux of water in the system (precipitation, combined sewer overflow, river flow) and (2) the number of fecal coliforms (cfu) per unit water.

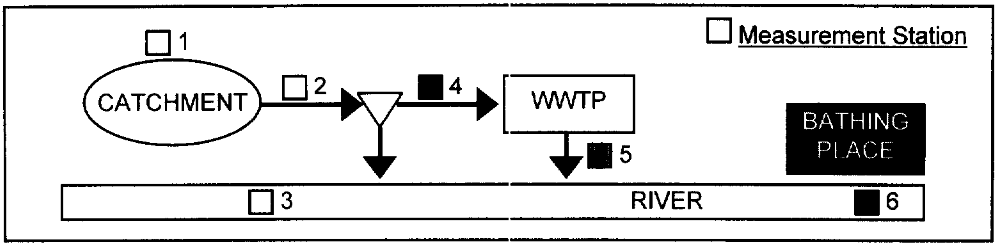

Figure 6. Scheme of the system and of the location of the measurement stations. The squares indicate the measured variables: white = flow or precipitation; grey = cfu and black = flow + cfu.

The design of the measurement campaign is dependent on both the physical outline of the system and the structure of the model. The first aspect determines at which location in the system measurements are possible and meaningful. The second aspect, the model structure, gives the information about the measurement variables and the measurement frequency at the different stations. A minimum measurement campaign for calibration of the hygienic hazard model is outlined in Figure 6.

According to the structure of the model the fecal coliform concentration in the raw sewage, the stormwater and the treatment plant effluent is considered to be constant. Hence, measurements of raw sewage (flow and concentration) and of WWTP-effluent can be done independently of the rest of the campaign. Alternatively, the data is directly derived from treatment plant data (locations 4 and 5). The concentration of fecal coliforms in the stormwater is usually very low as compared to the other two sources and it is therefore possible to use textbook values as a starting point (e.g. Rauch *et al.*, 1998a). Modelling the quantity of combined sewer overflow requires data from the rain-runoff process (measurement locations 1 and 2). In order to predict the mixing effect in the river it is also necessary to measure the river flow upstream of the drainage system. The measurement of flow and fecal coliforms at location 6 (Bathing place) is required in order to calibrate the model with respect to river flow and substance transport as well as to describe the disappearance of FC in the river. All measurements at locations 1, 2, 3 and 6 need to be made simultaneously during a rain event with a sufficient frequency to identify the dynamic behaviour of the system.

CASE STUDY III: TOTAL POLLUTANT LOSS REDUCTION

In the Trondheim project (Schilling *et al.*, 1998) an integrated model of the complete wastewater system was created, i.e. for sewage production, transport, and treatment. The system serves 38 km^2 and 135000 PE, and consists of 83 sub-catchments and 72 installations such as pumping stations, overflows and retention basins.

The task was to reveal the effects of various remedial measures to reduce the total pollutant loss from the system to adjacent receiving waters. Furthermore, reliable data on hydraulic and pollutant loads should be gathered for the design of a new treatment plant. Important processes to be included in the integrated model included storm water runoff and snow melt discharging directly into combined sewer systems or infiltrating into sewer pipelines, flow and retention in the collection network, backwater and sediment transport in the intercepting tunnel, and simulation of chemical treatment processes in the new plant.

Due to cost and time constraints the model was calibrated with historical measurements taken on a routine basis prior to the project and a few additional measurements as part of the project. Historical data included rainfall intensity at a gauge ca. 5 km outside the catchment, CSO duration registrations at some major overflows, pumping rates at some major pumping stations, and inflow measurements at the existing treatment plant. The dedicated measurements included a sampling campaign at the inflow of the existing treatment plant for two days in 2-h-intervals, and a visual inspection of tunnel sediments at two locations.

The model was calibrated with the data above and 4 historical runoff events. The overall performance of the model for the total catchment was surprisingly good, given the poor data base. Figure 7 shows an example for one of the runoff events. Figure 8 shows a dry-weather period where samples were taken. Note, that the flow gauge went out of operation during the most interesting period. As the model assumes constant concentrations of, both, sanitary sewage and runoff, the phosphorus peaks are not matching very well. The average concentration seems to match, though.

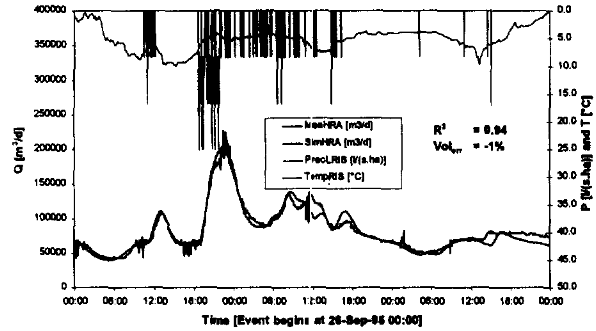

Figure 7. Measured versus simulated treatment plant inflow hydrograph for one of 4 calibration events.

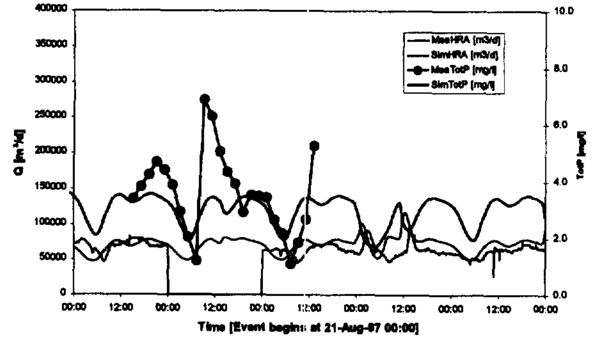

Figure 8. Measured versus simulated treatment plant inflow hydrographs and pollutographs for one short term sampling campaign.

Except for one sub-catchment, no overflow quantity or quality data was available. Thus, it was difficult to draw reliable conclusions for individual sub-catchments. Due to unavailable local rainfall data, wet-weather calibration could only be done with long-lasting and seemingly homogeneous rainfall events. The "calibration" of the sediment transport module was restricted to checking the long-term behaviour of the model in extreme situations (i.e. long dry-weather periods, large flows). Yet, even with the poor data background the model seemed to perform well. It was concluded, that only for the concrete planning of remedial measures in individual sub-catchments would additional field measurements be required.

CONCLUSIONS

The final steps in an 11-step model-based procedure for integrated wastewater management were covered in this paper. Especially the difficult task of collecting the necessary data for calibration/validation was focused upon. Recommendations were given to maximise the information retrieval from measuring campaigns. Especially the potential of an iterative procedure in setting up increasingly detailed measuring campaigns was stressed. It was shown that sensitivity analysis can support objective design of measuring campaigns.

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