A stochastic software tool to assess impacts of urban drainage on receiving waters

Un logiciel stochastique pour l'estimation des impacts des rejets pluviaux urbains dans les milieux récepteurs

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RESUME

De nouvelles directives ont été définies en Suisse mettant en relation les rejets urbains par temps de pluie et les impacts sur les milieux récepteurs. Le logiciel stochastique REBEKA 2 simplifie l'application de ces nouvelles normes. Le programme calcule au moyen d'une simulation de type Monte Carlo la probabilité que les critères soient respectés dans le milieu récepteur. L'utilisation de cet outil est présentée dans une étude de cas. Les résultats de simulation confirment les observations récoltées in-situ, à savoir que l'accumulation de MES dans le cours d'eau récepteur constitue le principal problème. L'application de ce programme montre qu'un modèle stochastique basé sur les impacts dans le milieu récepteur (approche de type immission) fournit une meilleure approche des problèmes que l'approche déterministe standard (approche de type émission).

ABSTRACT

In Switzerland new guidelines have been defined that relate wet-weather discharges from urban drainage with their potential impacts to receiving waters. The stochastic software tool REBEKA 2 simplifies the application of the new standards. The program calculates by means of a Monte Carlo simulation the probability that the immission-based criteria are met. The use of the software tool is presented in a case study. The simulation results confirm observations that TSS accumulation on the river bed of the receiving water for slack reaches is the main problem. The application of the program shows that immission-based stochastic modelling provides a deeper insight into the effective problems of receiving water impacts than the standard deterministic emission-based approach.

KEYWORDS

Combined sewer overflow, immission-based concept, model uncertainties, Monte Carlo simulation, stochastic modelling.

1   INTRODUCTION

Probabilistic methods are based on the realisation that non-point sources of pollutants in general, and urban wet-weather discharges in particular, provide highly variable inputs (concentration and loads) to receiving waters. They are generated intermittently at highly variable intervals, and when they do occur, are highly variable in both time and space. Furthermore, the impacts of non point sources are strongly influenced by significant differences in important characteristics of individual receiving waters and by inherent variability of natural water systems (EPA, 1989). For this reason, we have chosen to develop a probabilistic methodology for analyzing the water quality impacts of urban wet-weather discharges on rivers and streams (Kreikenbaum et al. 2002, Krejci and Kreikenbaum, 2004). In fact, in Switzerland, the project STORM has developed - in contrast to the traditional emission-based concept - new immission-based criteria for assessing impacts of urban drainage on receiving waters. Thus decisions on the impacts of wet-weather discharges upon beneficial uses can be made based upon in-stream water quality that has been estimated using a quantitative and qualitative model. A somewhat simplistic formulation of the management decision to be addressed by the STORM methodology is i) whether urban runoff decision is a significant contributor of pollutants in a particular river or stream, and ii) what level of control (CSO tank, BMP's…) will be required in order to meet specific water quality goals. In situation where urban wet-weather discharges cause an obvious negative impact, the answer to the first question is obvious. However, in most cases, such a determination is less obvious. In such cases, the use of specific software is necessary. For this reason, we developed the stochastic software tool REBEKA 2, based on STORM philosophy. This paper describes the concept and features of this software tool, its application in a case study and planned enhancements.

2   METHODOLOGY

2.1   Receiving Water Standards for Switzerland

Prior investigations (Gammeter, 1996; Krejci et al., 1994a, b) and results of the project STORM (Krejci et al., 2004; Rossi et al., 2004b) showed that impacts on rivers from overflows during wet weather are mainly caused by the following effects:
- Toxic concentrations of unionised ammonia;
- Erosion of the river bottom material;
- Total suspended solids (TSS):
  - Critical concentrations of TSS and adsorbed compounds in the receiving water;
  - Riverbed impairment: decreased river bed permeability due to excessive sedimentation (colmation), accumulation of toxic substances and accumulation of organic substances that can generate anoxic conditions in the river bed.

Therefore the project STORM defined new immission-based standards required to be met by discharges during wet weather. An application example of the standards is shown in the case study (see chapter 3). A more detailed discussion of the standards defined in the project STORM can be found in Rossi et al. (2004b) and Rossi et al. (2007).

2.2   Model description

The stochastic software tool REBEKA 2 used in this study is a further development of REBEKA (Rauch et al., 2002), a deterministic screening tool to assess impacts of urban drainage to receiving waters. REBEKA 2 takes parameter uncertainties of the underlying models into account and calculates by means of a Monte Carlo simulation

the probability that the immission-based criteria are met (Fankhauser et al. 2004). Probability distributions of the number of critical events per year for ammonia toxicity and riverbed erosion as well as total suspended solids (TSS) loads and time of critical TSS accumulation on the riverbed caused by urban storm water overflows are calculated. For simulating the systems variabilities, long time series of precipitation data are used as model input (10 years with a time resolution of 10 minutes).

Ammonia NH4-N concentration is computed by means of a simple mixing model, where constant concentrations are assumed in the baseflow, the storm water and the waste water. Total suspended solids (TSS) load is calculated by a stochastic approach (Rossi et al., 2005b).

Accumulation and erosion of TSS and degradation of organic matter are also modelled. The model does not account for a longitudinal sedimentation but assumes sedimentation at one virtual point. The resulting TSS density in the riverbed is calculated for each time step due to the described processes. This density is compared to defined thresholds for critical colmation and for toxicity. No impacts to the receiving water are expected if the thresholds are exceeded less than 20% of the annual time for colmation and less than 5% of annual time for toxicity.

The present structure of the program demands that the existing combined and separate sewer systems and the natural catchment have to be aggregated and described each by a linear reservoir. The most difficult part is the consideration of multiple overflow structures in the sewer system because only one overflow device per sewer system (combined and separate) is allowed. An analysis of the network by an emission-based simulation package like MOUSE, Hydroworks or SWMM may help to decide how to simplify the network .A workaround to this problem is (1) either to model the sewer system stepwise from the uppermost to the lowermost overflow structure taking the outflow from the first subsystem as constant inflow to the second subsystem etc. or (2) make a separate analysis of the importance of each overflow structure and based on these results simplify the system so that it can be modelled by REBEKA 2. This procedure is shown for the case study.

Although the used models are simple there are about 30 parameters that can be varied. It is therefore important to know which parameters have a high influence on the results. The built-in tool for sensitivity analysis allows an easy determination of important parameters for a specific task.

3   EXAMPLE OF APPLICATION

This case study was carried out as an example to demonstrate the application of the new immission-based standards defined by STORM and the use of the REBEKA II software. It will be published in the appendix to the new Swiss directive.
The investigated catchment is located in East Switzerland south of Lake Constance (Figure 1). A combined sewer system and a road drainage from the motorway A1 discharge to a small creek called Village Creek. The creek flows into Lake Constance. Because of lack of space we focus here on the impacts on Village Creek. The whole case study includes the discussion of impacts on the tributary area of Village Creek to Lake Constance.
The characteristics of the subcatchments and the associated overflow structures are summerised in table 1 (values from local drainage master plan in 2000). Values in brackets stand for full development in the future. The overflow structures of the first two subcatchments discharge into another creek called Goldach. The headwaters of Village Creek consist of two reaches rising at an altitude of 900 m. After the confluence of the two reaches above the motorway A1 (500 m a.s.l.) the creek flows through the urban area of Goldach and meets after 2 km Lake Constance near the

harbour of Goldach (ca 400 m a.s.l.). Average flow is estimated during dry weather to 30 - 50 l/s, low water discharge during summer to 10 - 20 l/s. The slope of Village Creek is despite of various drop structures relatively high (around 1 to 5 %). But for some sections the slope is so small that deposition of suspended solids occurs.

Subcatchment	drained Area [ha]	Inhabitants	Overflow Structure / Discharge		
			Name (Receiving Water)	V [m3]	Q ret [l/s]
Eggersriet	10.14 (9.13)	1620 (2130)	RB Eggersriet (G*)	435	32
Vogelherd	4.48 (3.47)	708 (1533)	RB Vogelherd (G)	170	180 (50)
Goldach A0	1.98 (1.71)	476 (630)	HE A0 (VC)	0	140
Goldach D6	5.97 (3.92)	1040 (725)	HE D6 (VC)	0	210
Goldach M15	6.92 (8.46)	1900 (2770)	HE M15 (VC)	0	360 (760)
Rietberg (Gold.)	4.95 (7.24)	1856 (2461)	RB Rietberg (VC)	120	90
Motorway A1	0.8 (0.8)	--	-- (VC)	0	--

Table 1: Characteristics of subcatchments and overflow structures (Values are taken from the drainage master plan, values in brackets are for full development in the future)
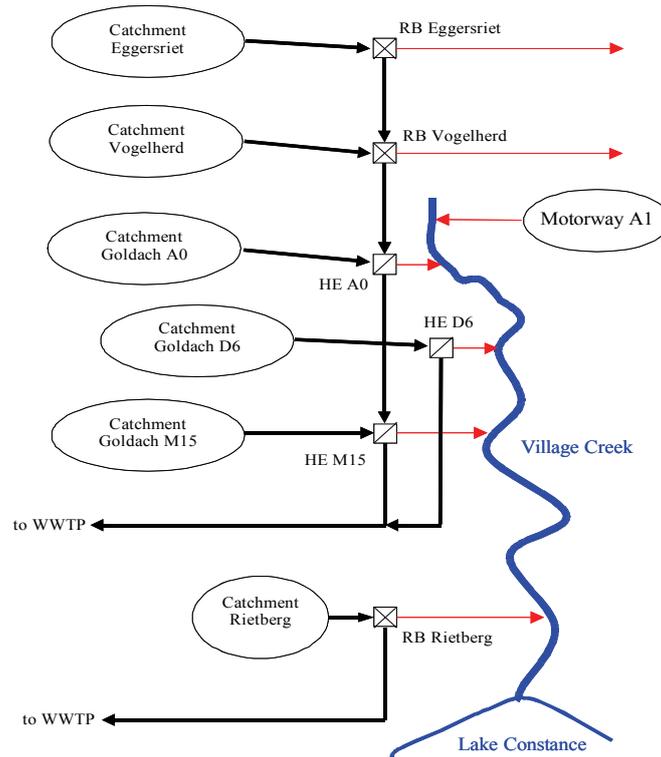*G: discharge to Goldach, VC: discharge to Village Creek

Figure 1: Catchments and combined sewer system discharging into Village Creek.

3.1 Prior Analysis of Discharges by Emission-based Simulation

As mentioned before the present concept of REBEKA 2 allows to model only one catchment with related CSO. In this case SWMM5 was used to preliminary analyse the discharges to Village Creek. Table 2 shows the results of the SWMM5 simulations for the actual and the future state (values in brackets). CSO 'D6' and 'RB Rietberg' are not considered in these simulations because the discharge of CSO 'D6' is negligible and that of CSO 'RB Rietberg' is only relevant for Lake Constance. The simulation results show that CSO 'M15' is most important ('RB Eggersriet' and 'RB Vogelherd' do not discharge into Village Creek.). So, the simplification of the network for REBEKA 2 can be accomplished as follows: (1) Separate simulation of Catchment Eggersriet with CSO tank 'RB Eggersriet'. (2) aggregating catchment 'Vogelherd', 'Goldach A0' and 'Goldach M15'. (3) taking the retained flow from CSO 'RB Eggersriet' (a result of step (1)) as inflow to the aggregated catchment.

CSO	Overflow characteristics			
	Volume [m3/a]	Frequency [1/a]	Duration [h/a]	TSS load [kg]
RB Eggersriet	28'000 (24'000)	32 (27)	127 (112)	2300 (2000)
RB Vogelherd	1000 (6000)	< 1 (16)	< 1 (57)	80 (450)
HE A0	300 (200)	3 (2)	16 (13)	30 (20)
HE M15	4000 (400)	7 (1)	8 (1)	400 (50)

Table 2: Results of SWMM5 simulation for the combined sewer system. Values in brackets are for the future state (full development)

3.2 Problem Identification and Need for Action

The urban area Village Creek is strongly straightened, has a fixed bed and is partially covered. Here, it serves as flood protection and receiving water of urban discharges. But according to the water status report the creek has also an ecological importance. It is regarded as a watercourse especially worthy of protection. Its fauna and flora are diverse. Its catchment above the motorway A1 is intact and mainly natural. In the urban area ecomorphological and chemical impacts are detected. The conclusions of the water status report suggest to check frequency and volume of CSO discharges and as short-term measures tanks for some CSO's. Concerning the road discharges from the motorway A1 measures to reduce the heavy metal load should be investigated. But primarily measures to enhance the ecomorphology and to create retreat spaces for aquatic life should be adopted.

Based on a simulation of the simplified sewer network by SWMM5 an additional ecological survey was conducted in April 2005. The encountered ecological deficiencies can be summarised as follows:

- *Ecomorphology:* Because of various drop structures the possibility of going upstream or retreating for fish and benthic organisms are strongly impaired. The ecomorphological state of the investigated creek section is heavily impacted and that of the upstream section is unnatural resp. artificial.

- *Hydraulic stress* is relevant for fish and other animals but their is currently a lack of information for an assessment of the problem.

- *Water quality:* Based on the analysis of diatoms (single-celled algae) water quality is rated rather poor.

- *Sediments:* Colmation of the river bed was found in slack sections directly downstream of CSO 'HE M15'. Iron sulphide (FeS) was also observed.

The impacts of the discharges from the motorway and the CSO 'HE M15' are especially identifiable by the colmation of the river bed.

Due to the investigations the need for action is indicated. The main objective of measures should be the reduction of TSS loads discharged into Village Creek by overflows during wet weather. The planning of measures and the priority ranking should be done based on a cost-benefit analysis.

3.3   Results of REBEKA 2 Simulations

Table 2 shows the simulation results for the actual and future state of the sewer system. We only present the probability of fulfilling aquatic life standards. The characteristics of Village Creek are chosen at a reach downstream of CSO 'M15' with a slope of 0.5%, a width of 2.5 m, a base flow of 20 l/s and a mean grain size of 1.5 cm. The results show that in the actual state the probability to meet the standards is low for TSS accumulation on the riverbed (toxic substances and oxygen criteria). The measures for the combined sewer system (future state) do not improve the condition of the receiving water because the main part of TSS emissions is caused by the drainage of the motorway A1. The discharged TSS loads from the various sources are summarised in table 4 and in figure 2. The calculated loads from the combined sewer system are in the same order as that calculated by SWMM5 (see table 2). The values in brackets show the variation due to different annual rainfall in the simulated period of 1995 to 2005.

Simulation runs	*Probability that aquatic life standards are met*			
	NH_3	*Colmation of the riverbed*	*Accumulation of toxic substances*	*O_2 Deficit due to organic compounds*
Actual state (1)	0.45	0.93	0.00	0.08
Future state (2)	0.52	0.95	0.00	0.08
Future state with road drainage treatment (3)	0.52	0.99	0.12	0.57

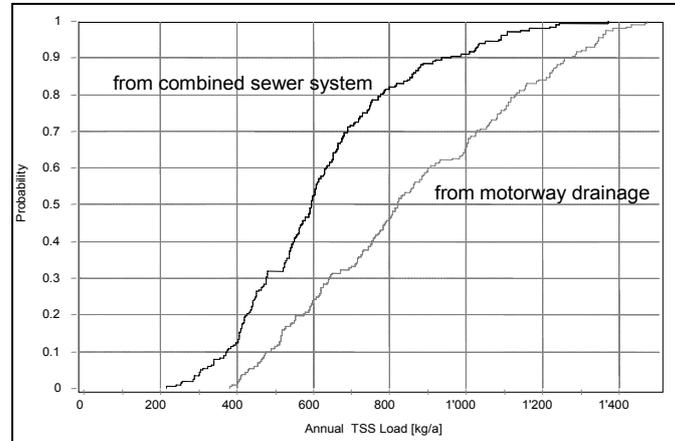Table 3: Results of the REBEKA 2 simulations for actual and future state

Figure 2: Cumulative probability for TSS loads to the receiving waters

The treatment of the road discharge (assumed removal efficiency of 80%) significantly improves the receiving water conditions but the accumulation of toxic sediments on the river bed for flat reaches remains a problem. The built-in sensitivity analysis shows that for slopes steeper than 1.8% the standards for toxicity are met.

Source of TSS emission	TSS emission [kg/a]		
	Actual state (1)	Future State	
		Without treatment (2)	With treatment of road discharge (3)
CSO 'A0' and 'M15'	567　(57 - 1689)	131　(0-491)	131　(0-491)
Drainage motorway A1	862　(621-1142)	862　(621-1142)	172　(124-228)
CSO tank 'RB Rietberg'	201　(24 - 613)	506　(183-1258)	506　(183-1258)
Total (sum of means)	1630	1499	809

Table 4: Discharged TSS loads to Village Creek calculated by REBEKA 2

Hydraulic stress was calculated for steeper slopes of 1 to 5% but even for these conditions the standards of less than 10 critical events per year (criterion defined for this specific case-study) were kept with a probability of 0.8.

4 DISCUSSION AND OUTLOOK

The REBEKA model provides a screening level methodology for determining the effects of intermittent pollutant discharges on the water quality of rivers and stream. The processes analysed in the model (urban runoff, stream flow, and water quality) are probabilistic by nature and are treated as such by the model. The method uses a probabilistic approach and accounts for the natural variabilities in the model inputs to estimate a cumulative probability distribution of in-stream effects due wet-weather

discharges into the stream. This model is not meant to replace more sophisticated deterministic or probabilistic models, but is an extremely useful screening level tool for initial planning purposes to help determine problem areas and to screen possible alternatives. The application of the software tool REBEKA 2 to the case study showed that immission-based stochastic modelling provides a deeper insight into the effective problems of receiving water impacts than the standard deterministic emmission-based approach. In the future additional processes can be included which turn out to be important for a realistic modelling of impacts. The built-in sensitivity analysis proved to be a good tool to calculate critical parameter values (e.g. river slope) that form the threshold for meeting the defined receiving water standards.

The use of REBEKA 2 forces urban water engineers to deal with uncertainty in planning of measures. The results are presented as probabilities that reflect the effect of model parameter uncertainties. The major drawback of the program is the fixed and limited catchment configuration that allows to model only sewer systems with a simple topology. A new program version is under development that allows an interactive construction of the system with combination of several catchments, overflows and receiving water discharge points.

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