Integrated model approaches for urban waste water systems and diffuse sources

Approches par modèles intégrés des systèmes d’eaux usées urbains et des sources diffuses

Michael Bach*, Dirk Muschalla, Kai Schröter, Manfred Ostrowski

Engineering Hydrology and Water Resources Management
TU Darmstadt, Petersenstraße 13, 64287 Darmstadt, Germany
*bach@ihwb.tu-darmstadt.de

RESUME
Cet article propose une approche intégrée de modélisation à l’échelle d’un bassin fluvial. Cette approche repose sur différents modèles de sous-systèmes d’un bassin fluvial : zones urbaines y compris les systèmes d’égout respectifs, les surverses d’égouts combinés et les usines de traitement des eaux, des bassins versants agricoles avec de sous-zones naturelles ou agricoles, et la masse d’eau de la rivière elle-même. L’article traite de la qualité de l’eau de tous les sous-systèmes parmi lesquels les sources de pollution diffuse y compris celles des zones agricoles et naturelles. L’approche par modèle est appliquée au bassin versant de la Région de Hesse en RFA. Cette approche permet de reproduire les procédés dans le bassin fluvial et les interactions entre ses différents sous-systèmes.

ABSTRACT
An integrated approach for river basin wide modelling is proposed. The approach is based on different models for the sub systems of a river basin: urbanized areas including respective sewer systems, combined sewer overflows and waste water treatment plants; rural catchments with natural or agricultural sub areas and the river body itself. Impacts on water quality from all sub systems are considered including diffuse pollution sources from agricultural and natural areas. The model approach is applied to a catchment in the Federal State of Hesse, Germany. The approach is capable to reproduce processes within and interactions between the different sub systems of a river basin.

KEYWORDS
Diffuse sources ; point sources ; river basin wide integrated modeling.
1 INTRODUCTION
The implementation of the Environmental Framework Directive (WFD) includes new provisions to regulate pollution by diverse substances and sources (EU, 2000). This comprises the establishment of a combined approach, which permits the use of both environmental quality standards and fixed emission limit values. The dominant objective of the WFD is to achieve a “good ecological and chemical status” by means of river basin management plans. However, many water bodies do not meet the desired water quality as well as morphological and biological quality criteria.

Often, river basins are formed by a patchwork of urbanized, agricultural and natural areas (Andrieu and Chocat, 2004). As shown in Fronteau et al. (1997), optimum management of individual systems does not necessarily yield optimum performance of the entire system. Therefore, integrated river basin wide models need to describe impacts from all areas to understand the complex interactions between different catchment parts and to plan and design mitigation measures.

Various interactions exist between the different sub systems of a river basin. For example, the effluents from point and diffuse sources are superimposed in the water body. Effluents from urban areas can be diluted by the runoff from natural areas. Regarding hydraulic stress and nutrient concentrations, the impacts of several urbanized areas can interfere with each other and the rural environment. To understand the interactions between the different sub systems and to establish reasonable mitigation measures, a river basin wide model is desirable and needed. A general outline for a river basin wide model approach was given in Ostrowski and Schröter, 2004.

1.1 System description
Figure 1 outlines typical sub systems of a river basin to be included in a river basin wide integrated model approach. This comprises urban areas with their sewer systems, waste water treatment plants (WWTP), rural catchment parts with natural or agricultural areas and the receiving water bodies.

![Figure 1: Sub systems of a river basin](image)

1.2 Impacts
A water body is exposed to various impacts, normally grouped into point and non point or so called diffuse pollution sources. All wastewater that reaches a water body via combined sewer overflows (CSOs), WWTPs or other specific entry points such as industrial effluents, is regarded as point source. All remaining impacts are subsumed into diffuse sources.
Diffuse sources are mainly surface runoff including erosion, interflow and groundwater flow. They load the receiving water body with nutrients, pesticides and other hazardous substances. Due to the reduction of point sources achieved by upgraded WWTP and rehabilitation of sewer systems, the impacts of diffuse sources are of increasing importance to further improve the ecological status of natural water bodies (Mailhot et al., 1997).

2 INTEGRATED MODELLING
The topic of integrated modelling of urban water systems was first raised by Metcalf and Eddy (1971), Beck (1976), Lijklema (1989) and Lijklema et al. (1993). Integrated modelling is often defined as the linkage of at least two physical systems out of the three components sewer system, WWTP and receiving water body. Harremoës (2002) concluded that the majority of integrated models for urban waste water systems coupled only two sub systems and that there was no integration of rural or natural catchment parts at all. Today, one can find several integrated model approaches that couple more than two sub systems. Schütze et al. (2002), Vanrolleghem et al. (2005) and Muschalla (2006) integrated the sewer system, the WWTP and the receiving water body in various complexity. However, all of these model approaches consider only one urban area with its sewer system and WWTP in detail. Consequently, the impact and planning of measures for only one urban area can be assessed at one time. Flow and pollution information stemming from upstream agricultural, natural or urban areas are normally considered in a simplified, often aggregated, manner.

Looking at models for rural areas one can find a large variety of approaches for the estimation of diffuse pollution sources, ranging from field (micro) scale up to river basin (meso) scale. The models operating at river basin scale mainly focus on average yearly, monthly or daily loads. Only a few models are working with an adequately fine temporal resolution that allows to account for effects of single rain events, see e.g. ANSWERS2000 (Bouraoui and Dillaha, 2000). The representation of urban areas is not possible in most models and if so (e.g. HSPF (Bicknell et al., 2001), SWAT (Arnold and Fohrer, 2005)), urban impacts are represented in a most simplified manner only.

It can be stated that there is a lack of river basin wide modelling tools considering all four sub systems, probably due to the following reasons:

- The responsibilities for planning and management of sewer systems, WWTP and water bodies have been splitted between different authorities in most European countries (Rauch et al., 2002).
- Models for the different sub systems have been developed independent from each other. Thus, different concepts, model approaches and different state variables are used to describe processes in the different sub systems, hampering the linkage of models (Fronteau et al., 1997).
- Model complexity and data demand fundamentally increase with the inclusion of more and more sub systems (Rauch et al., 2002).

3 MODEL APPROACH
The model approach proposed is based on a sequential combination of models for each sub system of a catchment: Urban areas, rural and natural areas and the water body itself. To account for the high dynamics of CSOs, all sub systems use a simulation time step of five minutes.
3.1 Urban Areas
For urban areas (including all CSO structures and the WWTP) the pollution load model SMUSI (Mehler et al., 1998) is used. It is a conceptual hydrological model and considers three sources of pollutants: Runoff from pervious areas is considered as unloaded, a constant surface runoff concentration based on an annual pollution load potential is assumed for the wash off from impervious areas and predefined time variable concentrations are assigned to the dry weather flow of domestic waste water. Modelled parameters are biological and chemical oxygen demands (BOD, COD), ammonium, phosphate, total organic carbon and suspended solids. Effluents from the WWTPs are not modelled explicitly but based on monitoring data available from the operators of the WWTPs.

3.2 Rural and natural areas
Runoff and flood routing processes of the natural and agricultural areas are modeled separately from the processes of pollutant concentrations.

The model TALSIM (Lohr, 2001), a spatially distributed long-term hydrological model is used to calculate the runoff based on soil moisture processes and unsteady flood routing in the receiving water body.

Pollutants stemming from agricultural areas are estimated for surface runoff, interflow and groundwater flow, respectively. Erosion is the main source of pollution associated with surface runoff. Mean erosion values are used depending on soil types (Kraft, 2001). Nutrient concentrations are assigned based on land use according to (Hamm, 1991). Retention of eroded material and nutrient enrichment processes are accounted for according to Auerswald (1989). The land use type is most important for pollutant washout into interflow and groundwater flow. Empirical values of nitrogen and phosphate were assigned for each land use type as given in Firk and Gegenmantel (1986).

The chosen approach can be classified as variable discharge with constant pollutant concentration. The pollution concentrations are derived for each sub system individually, thus the spatial variation of impacts is considered.

3.3 River Course
The dynamic compartment model WASP (Wool et al., 2005) is used for the modelling of water quality processes in the receiving water body. The water body is divided in different segments and the reaction processes are simulated for each segment based on the continuous stirred tank approach. Processes considered are reaeration, decomposition of organic material and nitrification. As flood routing processes are not included in WASP, necessary information (volumes, velocities and water levels for each segment) are calculated with TALSIM and imported into WASP via an interface.

3.4 Integrated Model
Figure 2 shows a scheme of the integrated model. The different sub models are marked with dashed lines, solid line rectangles state processes within the sub models. Interfaces between sub models are drawn with elliptic lines. Arrows indicate the information flow from one sub model to another. The respective information passed is annotated to the arrows. Flow information of the WWTPs, natural and urban areas are superimposed in the TALSIM model and define continuous variable boundary conditions for water quality processes in the river course. Pollution loads of CSOs, WWTP effluents and from rural and natural areas are transferred into WASP as time variant concentrations.
The model is able to represent several urban areas within one catchment, each with sewer system and WWTP.

Figure 2 : Integrated Model Approach
x: Place, t: Time, C(x,t): Concentration, Q(x,t): Runoff

4 CASE STUDY

4.1 Catchment
The model approach was applied to the catchment of the upper Modau river (Hesse, Germany). The catchment size yields approximately 37 km² and the length of the river course is about 14 km until it reaches a retention basin. Parts of the catchment are intensively used agriculturally and four urban areas (see Figure 3) are located within the catchment. Aside from the diffuse sources, there are 15 CSOs and two WWTPs within the catchment.

4.2 Model setup
The river course was divided into six segments (see Figure 3). Accordingly, the contributing sub catchments were derived. For each sub catchment the relevant values regarding diffuse pollution were determined. As WASP can handle only one boundary element defining lateral inflow and boundary concentrations for a segment, the CSOs of each sub catchment were superimposed with flow and diffuse pollution concentrations from rural areas and WWTP effluents (Interface MIX, Figure 2).

4.3 Results
Figure 4 shows the inflow of segments 1 – 3. The hydrograph shows the flow reaction for several rain events during the one week period examined. Only during the third peak (13.04.1997), the CSOs of the urban areas were activated, whereas no CSO discharges took place during the remaining rain events.
Figure 3: Land use distribution

Figure 4: Discharge in segments 1 to 3

Figure 5 shows the ammonia concentration versus time in segments 1 to 3. The WWTP in Brandau is emitting an effluent with higher ammonia concentration than the inflow from the surrounding catchment. Thus, the runoff from the rural areas of the catchment dilutes the ammonia concentration in the river course. The peaks in segment 3 are caused by runoff from sub catchment 3 having a higher ammonia concentration than the discharge from the upstream catchment. The runoff from the rural areas of sub catchment 3 that has no CSOs reaches the river course earlier than the upstream discharge peaks. Thus the ammonia concentration increases before the off peak of the hydrograph reaches segment 3.
The results demonstrate that the model approach developed is capable to plausible estimate important impacts and interactions between different sub systems of a river basin with mixed land use and several urban areas.

5 CONCLUSIONS
An integrated river basin wide modeling approach including diffuse sources and multiple urban areas was developed. The model approach is capable of reproducing processes within and between different sub systems of a river basin, that are urban areas with sewer system and CSOs, WWTPs as well as runoff and pollutants from agricultural and natural areas.

The estimation of loads from diffuse sources was difficult due to limited data availability. Thus, it was only possible to include constant diffuse pollution concentrations at present. However, the obtained results emphasize the necessity of such an integrated model approach. It is a promising tool for the investigation of water quality problems, of interactions between different sub systems at river basin scale, of related knowledge gaps and data needs.

At the moment, work is carried out to enhance the integrated catchment model approach. In particular, the following topics are addressed:
- Integration of variable diffuse pollution concentrations;
- Enhancement of the model for a more detailed representation of CSOs. As described in Klawitter (2006), a detailed spatial representation of the CSO structures in a model is strongly reducing the overflow peaks compared to a superimposed discharge at a single point;
- Automated linkage possibilities between the different sub models, e.g. via the OpenMI interface (Roger Moore, 2005).

6 LIST OF REFERENCES


