International Environmental Modelling and Software Society (iEMSs)
2012 International Congress on Environmental Modelling and Software
Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany
R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.)
http://www.iemss.org/society/index.php/iemss-2012-proceedings

Validation and Sensitivity of a Coupled Model Tool for CSO Impact Assessment in Berlin, Germany

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Abstract: In the city of Berlin combined sewer overflows (CSO) can lead to severe depressions in dissolved oxygen (DO) of receiving urban rivers and hence to acute stress for the local fish fauna. To quantify CSO impacts and optimize sewer management strategies, a model-based planning instrument has been developed. It couples the urban drainage model InfoWorks CS which simulates hydraulics and pollutant transport in the sewer with the river water quality model QSim which simulates hydraulics, mass transport and various biogeochemical processes in the receiving water body. To identify simulated CSO impacts, concentration-duration-frequency-thresholds for DO are applied to river model results via an impact assessment tool. Two kinds of impacts are distinguished: i) suboptimal conditions and ii) critical conditions for which acute fish kills are possible. In the case of Berlin, suboptimal conditions are observed on up to 92 days per year, predominantly during periods of low discharge and high temperatures whereas critical conditions only occur after CSO. For model calibration and validation, continuous measurements in both river and sewer are used. First simulations show good accordance between simulated and measured DO concentration in the river with Nash-Sutcliffe efficiencies between 0.70 and 0.79 for an eight-month time period at three different river monitoring points. However, to assure satisfactory model performance for adverse DO conditions in particular, impact assessment results for measured and simulated data are compared. Regarding suboptimal DO conditions simulated and measured data show good agreement. Nevertheless model representation for critical conditions is poor for some river sections and requires further improvement for CSO conditions. The results underline the importance of combining different validation approaches when dealing with complex systems.

***Keywords**: Combined sewer overflows; dissolved oxygen; impact assessment; model validation; sensitivity analysis*

1 INTRODUCTION

In the city of Berlin regular combined sewer overflows (CSO) lead to acute stress of aquatic organisms in the receiving River Spree and its side channels. Of most concern is the occurrence of depressions in dissolved oxygen (DO), which has been acknowledged as a major issue in the Berlin inventory for the EU Water Framework Directive [2004].

To assess the impacts of CSO on the Berlin River Spree a model-based planning instrument has been developed. It will be used by decision makers to study different sewer management and climate change scenarios. The planning instrument couples

i) the sewer model InfoWorks CS [WSL 2004], which simulates volumes and substance loads of CSO,
ii) the river water quality model Hydrax/QSim [Kirchesch and Schöl 1999; Oppermann 2010] which simulates the effects of these CSO on hydraulics and water quality in the receiving water body and
iii) an impact assessment tool which evaluates and quantifies the simulated effects of CSO on the receiving river.

Before employing the coupled model-tool for prediction of CSO impacts in the river, calibration and validation has to be conducted. Both procedures are particularly important when different models are coupled and uncertainties on process variables, input data or model structure may add up. The assessment of the model performance is a fundamental part of calibration and validation, typically basing on two approaches: i) the subjective (or qualitative) evaluation of the model behaviour via visual inspection of simulated and observed hydrographs and ii) the objective (or quantitative) evaluation by means of mathematical error estimation methods that quantify the deviation between model results and measurements [Krause et al. 2005].

However, both methods might be insufficient in the case of the above described planning instrument for CSO control. For instance, river model performance regarding state-variable DO might be poor in visual terms, e.g. due to a delayed simulation of the resulting DO sag after CSO, but nonetheless simulations and measurements agree on the frequency of adverse DO conditions. On the other hand, model efficiency according to objective goodness-of-fit measures, e.g. the coefficient of determination r^2 or the Nash-Sutcliffe efficiency E [Nash and Sutcliffe 1970] could be identified as satisfactory over the simulated time period, even though critically low DO values after single CSO events are not simulated properly. As a consequence, the use of impact assessment parameters, such as the number of days with suboptimal or critical DO conditions, is introduced as a supplementary step for model validation throughout this paper.

First applications of the planning instrument aim at testing the sensitivity of the model output to changing boundary conditions. Different sewer management solutions such as the increase of storage volume, the reduction of the impervious area, decentralized treatment of storm water runoff or end of pipe treatment of overflow water will be combined with expected climate change effects like temperature rise or change in rainfall intensity and analysed with the coupled model tool. Once the simulated CSO impacts in the river fit well with the observations, the model tool can support decision makers in finding appropriate sewer management strategies or analyse the effect of future climate change.

2 STUDY SITE

The combined sewer system of the city of Berlin covers a drained area of approximately 100 km² and collects storm water and sewage of 1.5 million inhabitants via a sewer network of 2,000 km length. After intense rainfalls the 180 CSO outlets located along the River Spree and its side channels can become a major source of pollution. According to estimations of the Berlin water utilities 20 to 30 CSO events per year are counted on average. However, CSO frequency strongly depends on the spatial and temporal distribution of rainfall and on the specific properties of each sub-catchment (e.g. storage volume, size of drainage area, runoff coefficient).

The receiving River Spree is a flow-regulated lowland river of 50 to 70 m width and 2 to 3 m depth. It has an average monthly discharge between 12 and 45 $m^3 s^{-1}$

(time period: 2000 to 2010) with flow velocities between 6 and 24 cm s^{-1}. The Berlin section of the River Spree is strongly affected by various human activities leading to a highly degraded river morphology, homogeneous river substrates and reduced biodiversity [Leszinski et al. 2007]. Periodic CSO events implicate additional stress to the ecology of the urban water courses.

The simulated stretch of the River Spree and its side channels has a total length of 27 km and receives storm water and sewage from 67 CSO outlets each of which is represented in both the urban drainage model and the river water quality model (Figure 1).

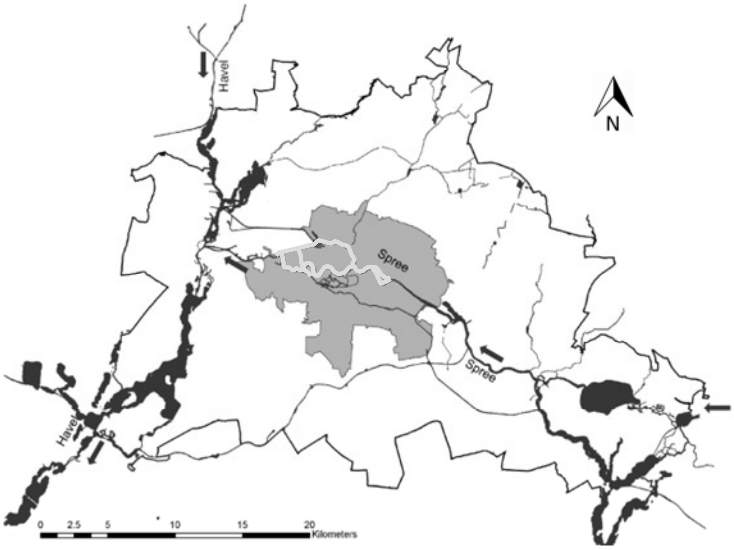

Figure 1. Map of the city of Berlin with its main waterways (black), the combined sewer area (dark grey area) and the simulated river stretch (light grey lines).

3 MATERIAL AND METHODS

3.1 Dynamic models

Since the Berlin sewer system is highly complex with little slope at most reaches, flow in the sewer is simulated hydrodynamically with the software package InfoWorks CS [WSL 2004]. InfoWorks CS solves the full St. Venant equations and thus accounts for backwater effects and reverse flow, both of which occur in the Berlin sewer system. In terms of pollutants it simulates the transport of dissolved and solid fractions of biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonium (NH_4), total Kjeldahl nitrogen (TKN), total suspended solids (TSS), total phosphorus (TP) and ortho-phosphate (PO_4). Degradation processes are not considered assuming that the travel time in sewers is too short for significant decay of constituents. The Berlin model is calibrated and validated based on measurements taken with online probes in a major overflow sewer [Caradot et al. 2011].

For the simulation of DO dynamics in the river, the hydraulic model Hydrax [Oppermann 2010] with the coupled complex water quality model QSim [Kirchesch and Schöl 1999], developed at the German Federal Institute of Hydrology (BfG) were chosen. The hydraulic model Hydrax solves the full St. Venant equations and allows simulating various special features that affect river hydraulics, such as macrophyte cover or spur dykes. The water quality model QSim calculates one-dimensional transport and reactions of all major water quality parameters, covering a great number of biological parameters, including both planktonic forms that move with the water (green algae, diatoms, cyanobacteria and rotifers) and sessile species (benthic algae, macrophytes and filter feeders) [Schöl et al. 1999; Schöl et al. 2002]. For model calibration and validation long-term continuous measurements at several river points are considered.

For the link between the sewer and the water quality model, each of the 67 CSO outlets simulated with InfoWorks CS is represented by a separate inlflow in Hydrax/QSim to resolve the spatial distribution of CSO impacts along the river. Although the sewer model simulates the most critical parameters for DO depressions in the river (e.g. BOD, COD, TSS, NH_4) it does not cover all state variables of QSim. Accordingly, assumptions have been made on parameters such as phytoplankton (which is probably close to zero in the sewer) or DO (which is assumed to be 0 mg L^{-1} in CSO).

3.2 CSO impact assessment

Regarding impact assessment the quality standards proposed by Lammersen [1997] for lowland rivers are applied to measured and simulated water quality data of the River Spree. The Lammersen-approach defines DO thresholds for eight exposure durations ranging from 10 minutes to 24 hours (Figure 2). For each threshold temperature-dependent correction factors are used, since the oxygen demand of aquatic organisms depends on the water temperature [Downing and Merkens 1957]. The protocol aims at protecting fish and invertebrates from any adverse effect ranging from impairment of swimming behaviour to death. Throughout this paper, a time period is classified as an event with suboptimal conditions, when at least one of the eight concentration-duration-criteria is met.

In addition to these suboptimal conditions, the LC_{50}-value of the asp (*aspius aspius)*, the fish species of the River Spree that is most sensitive to low DO, was chosen as a second quality standard for highly critical conditions. If DO concentration remains below 2 mg L^{-1} for more than 30 minutes, lethal impacts on aquatic organisms have to be expected. This approach follows Buikema and Benfield [1980] who suggest to focus on the requirements of the least tolerant species, to protect the local biocenosis as a whole. Figure 2 illustrates the quality standards for both suboptimal and critical conditions.

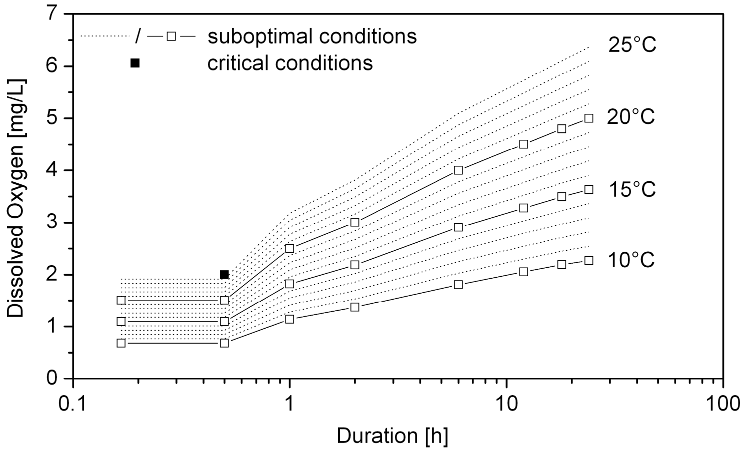

Figure 2. Quality standards for CSO impact assessment. Thresholds for suboptimal conditions are adapted from Lammersen [1997] and are defined as a function of duration and temperature. The threshold for critical conditions refers to the LC_{50}-value of the asp (*aspius aspius*).

To provide a semiautomatic and standardised tool for the evaluation of model results a database application for CSO impact assessment has been developed. The application provides a graphical interface allowing the user to select the simulated DO time series of a certain scenario. The chosen time series is then analysed by successively comparing it to the quality standards described above. Results are provided in terms of tables and graphs, displaying the number of events and calendar days with suboptimal or critical conditions at different points in the River Spree. The impact assessment tool was established primarily for comparison of scenarios regarding their impact in the river. However, it also allows validation of model results with respect to the occurrence of suboptimal/critical DO conditions.

4 RESULTS AND DISCUSSION

Coupling of the sewer and the river water quality model has been successfully demonstrated for the eight-month time period April to November 2010.

4.1 Sewer model

In the time period April to November 2010 a total CSO volume of 2.9 million m³ was simulated to have entered the River Spree. Half of that volume was discharged during only five CSO events. For an exemplary storm event on 23 July 2010 sewer simulations with InfoWorks CS identified an overflow volume of 4,480 m³ and pollutant loadings of 51 kg, 251 kg and 811 kg for BOD, COD and TSS at a monitored CSO outlet at km 9.7 of the modelled river stretch. Figure 3 shows the rain intensity and the simulated and measured water flow (left panel) as well as the simulated and measured loadings of TSS (right panel) at the observed outlet.

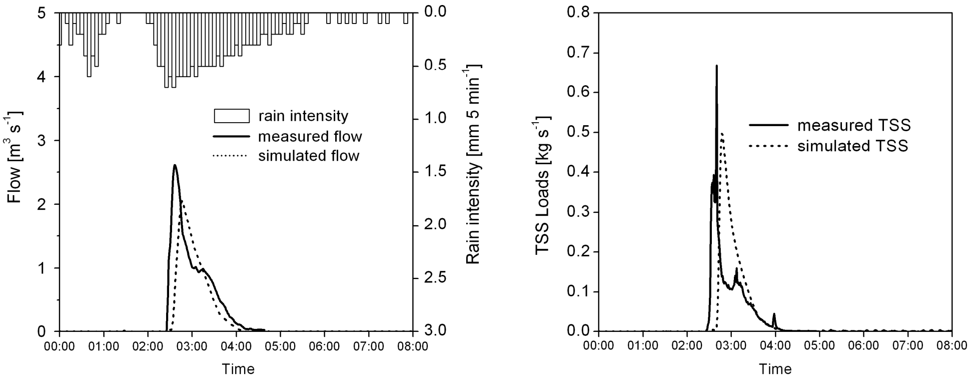

Figure 3. Measured and simulated water flow (left panel) and loadings of total suspended solids (TSS) (right panel) at a major overflow sewer during a storm event on 23 July 2010 with a total rain height of 22.7 mm.

4.2 Coupled sewer and river model

The seasonal pattern of goal state variable DO is well represented by the coupled model for the entire simulated time period (Figure 4, left panel). Quantitative evaluation of model performance yielded Nash-Sutcliffe-efficiencies between 0.70 and 0.79 at different monitoring stations. Looking at the specific CSO event shown in Figure 3, the river water quality model QSim shows a significant drop in dissolved oxygen to 3.5 mg L^{-1} at km 10.3 of the modelled river stretch 600 m downstream of the CSO structure (Figure 4, right panel, dotted line). However, visual inspection shows that DO depression in the River Spree is not simulated to the same extent as indicated by measurements. In particular, the lowest DO occurrence is not met by the model. Thus, satisfactory Nash-Sutcliffe-efficiencies obtained for the eight-month simulation period described above do not necessarily imply that all observed DO depressions can be properly predicted with the model tool.

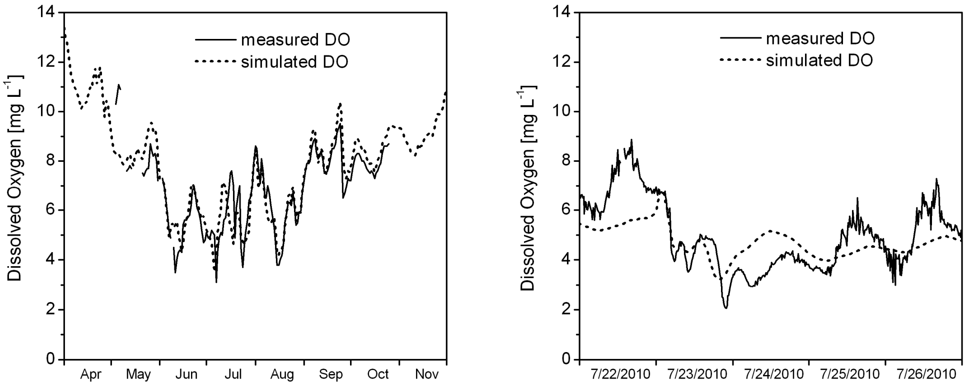

Figure 4. Measured and simulated concentrations of dissolved oxygen (DO) at a CSO affected river point. The left panel shows daily averages for the eight-month period April to November 2010. The right panel shows 15-min-values during a storm event on 23 July 2010.

4.3 CSO Impact assessment

Applying the two impact assessment approaches described above to measured and simulated data of the year 2010 shows good agreement regarding encountered suboptimal DO conditions (Figure 5, upper panel). According to simulations, DO concentration has been low enough to potentially harm aquatic organisms on 50 to 54 calendar days, whereas measurements indicate between 34 and 50 calendar days with suboptimal conditions depending on the river section looked at. However, the coupled model tool shows significant drawbacks when it comes to representation of critical DO conditions (DO < 2 mg L^{-1} for ≥ 30 minutes). While such conditions are measured on up to 4 days at a highly CSO-influenced river section in the city centre (km 4.8), simulations show no critical conditions at all (Figure 5, lower panel), indicating insufficient model representation of low DO concentrations. Since the occurrence of DO concentrations below 2 mg L^{-1} is the main reason for occasional fish kills in the Berlin River Spree, further improvement is necessary to obtain a reliable instrument for CSO control.

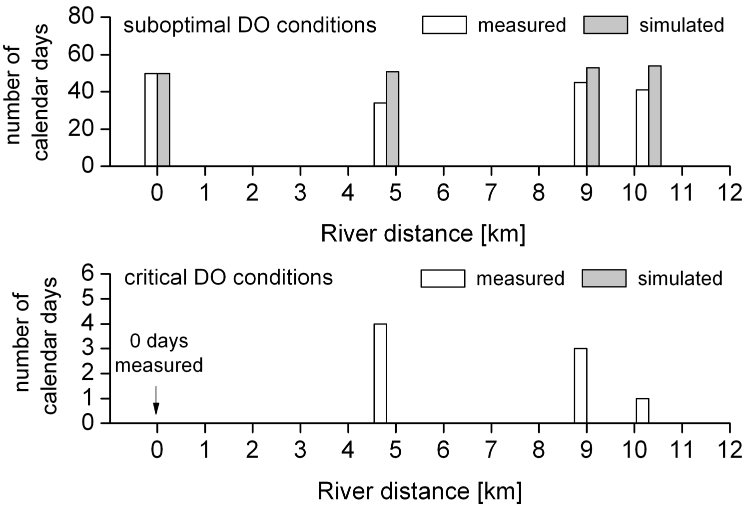

Figure 5. Quantification of suboptimal (upper panel) and critical DO conditions (lower panel) at four locations along the river (km 0, km 4.8, km 9.0, km 10.3) according to measured and simulated data for 2010.

4.4 Model sensitivity

Both the sewer and the river water quality model have been successfully calibrated to dry weather conditions. Currently, improved calibration to CSO conditions is conducted for both models. When calibration aims at adapting urban drainage parameters, it has to be assured that not only the sewer but also the river water quality model reacts sensitively regarding goal state variable DO. Sensitive behaviour to changing model input is not only fundamental when calibrating a model. It is also the basic prerequisite for using the model tool for the comparison of different sewer management and climate change scenarios. Again, the sensitivity of simulated impacts in the river to changes in boundary conditions should be assessed by looking at both DO concentration and the number of days with suboptimal or critical conditions.

First results on the sensitivity of goal variable DO to CSO pollutant concentrations show that for the tested range of input values the minimum DO concentration simulated in the river nearly depends linearly on the biochemical oxygen demand (BOD) simulated in spill water (Figure 6, left panel). Changes in river model input via adaptation of the sewer model can improve representation of CSO impacts in the river. For the studied storm event on 23 July 2010, a BOD increase of 100 % (e.g. due to sewer model calibration) would lead to a decrease of the lowest DO concentration by 40 % (Figure 6, right panel, dotted line). Hence, DO in the river would remain below 2 mg L^{-1} for more than 30 minutes, better agreeing with measurements on the occurrence of critical DO conditions.

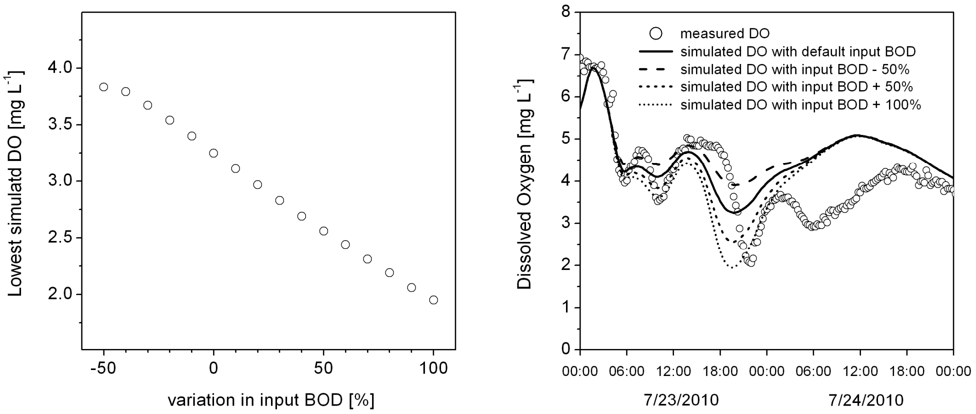

Figure 6. Sensitivity of dissolved oxygen (DO) in the river to changing biochemical oxygen demand (BOD) in CSO for a storm event on 23 July 2010. Left panel shows the lowest resulting DO concentration for different BOD input concentrations. Right panel shows measured and simulated DO time series for four different BOD input concentrations.

5 CONCLUSIONS

The results indicate that the simulation of CSO impacts in receiving rivers is possible at good quality through the coupling of a sewer model with a river water quality model. Even for complex urban water systems such as the Berlin River Spree, highly interdependent state variables such as DO can be simulated at high temporal resolution. Classical validation of model results by visual evaluation and the use of conventional goodness-of-fit measures demonstrated good agreement with DO concentrations measured in the river. In contrast, application of legislative goal functions revealed shortcomings in the performance of the model tool. The four most severe DO depressions observed in the studied 8-month time period could not be represented by the model tool. While these four depressions were rather short with a total duration of only 24.5 hours, they are expected to be most critical for the river ecosystem. Since the improvement of the ecological quality is the main objective of the future use of the coupled model tool, further development is necessary regarding the representation of such situations.

We conclude that coupled model tools can be valuable instruments for decision makers to find appropriate strategies for CSO control or to analyse the expected impact of climate change on the river. However, for validation of model results it is crucial to compare model output and measurements with regards to legislative goals in addition to conventional validation methods. By that it can be provided that the planning instrument is able to meet the specific requirements of CSO representation. Once the model tool is validated, its sensitivity to realistic changes in boundary conditions such as the increase of storage volume or the reduction of the impervious area needs be tested. The analysed change scenarios should be developed in close cooperation with local decision makers to provide that only realistic solutions or effects will be considered already at the testing stage. Only after validation with legislative goal functions and sensitivity analysis for feasible change scenarios, the model tool should be used to support specific planning.

ACKNOWLEDGMENTS

The presented work is a result of the KWB research project MIA-CSO and the EU FP7 project PREPARED. Modelling and monitoring efforts in Berlin are financially supported by Veolia Water, Berliner Wasserbetriebe and the Berlin Senate Department for Urban Development and the Environment. We kindly thank Volker Kirchesch and his colleagues at the German Federal Institute for Hydrology (BfG) for the constant development and support regarding the modelling software QSim.

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