Construction and calibration of an integrated urban drainage model

C. Fronteau, A. Van Griensven, W. Bauwens
Laboratory of Hydrology, University of Brussels (VUB), Pleinlaan 2, B-1050 Brussels, Belgium
EMail: fronteau@vub.ac.be

Abstract

An integrated system in Flanders consisting of a sewer, a wastewater treatment plant and a river component is selected for a modelling project. The purpose of the study is to assess the impact of combined sewer overflows on the receiving water and to investigate on the effects of different operating scenarios within the sewer system. Commercial mathematical models are used, i.e. both the sewer network and the wastewater treatment plant are modelled with Kosim, while Isis is used to represent the river system. The paper will mainly focus on the calibration process of the integrated model. Hydraulic measurements were carried out in the sewer system over a period of 6 weeks and overflow volumes and loads, together with river pollutant concentrations upstream and downstream of the overflow, collected for several events. Wastewater treatment plant influent and effluent data is available for the calibration of this sub-model. Finally, river flows are continuously registered at several locations and a sampling campaign resulted in quality data. Conclusions are formulated towards the amount of data needed for the calibration of integrated models and the use of commercial software for integrated modelling studies. Finally, thought is given with respect to the required complexity of integrated models.

1 Introduction

The combination of both sewer, wastewater treatment plant and river model results in an integrated model that allows for the transient flow and load characteristics in the overall urban drainage system to be considered. Simulations are performed sequentially and also continuously in order to take into account
flow and climatological changes. A holistic approach is necessary to include the risk that a combination of factors leads to a critical situation that can hardly be assessed when focussing on a part of the system only. Integrated modelling allows for an analysis of water quality problems in agreement with the Environmental Quality Objective/Environmental Quality Standard (EQO/EQS)\(^1\). Statistical analysis of immission characteristics of the receiving waters, resulting in concentration-duration-frequency curves, can be performed in the analysis of the effects of different pollution abatement scenarios. These curves make it possible to gain insight in the duration and the frequency of occurrence of events with a non-allowable pollutant concentration.

2 The integrated system

![Figure 1: The Zwalm catchment in Flanders](image-url)
The sewer system of Brakel, a village in Flanders at about 50km west from Brussels, drains an area of 200ha of which 25% is impervious. The connected population equivalent equals 4000. The network is built out of 370 pipes and manholes and contains 20 hydraulic structures. Two trunk sewers, one along the river Molenbek and another along the river Dorenbosbeek, collect the mixed water to lead it to a wastewater treatment plant (WWTP). The plant discharges its effluent into the river Zwalmbeek about 300m downstream of the point where the rivers Molenbeek and Dorenbosbeek meet. The overflow under study (i.e. structure 1529.2) is discharging into the river Molenbeek at its downstream end (Figure 1).

The wastewater treatment plant of Brakel is designed for a population equivalent of 7000. The maximum discharge that is biologically treated amounts to 661/s (i.e. 2.5 DWFn). The excess flow is collected in a rainwater tank with a maximum flow of another 661/s. The rainwater stored in the basin is treated whenever allowed by the treatment capacity (during dry weather).

The Zwalm catchment that has an area of 114km² is part of the larger Scheldt catchment. The river Zwalm has a length of 21.75km, a slope of 3.8% and its average annual discharge equals 1.14m³/s.

![Graph](image-url)
3 The integrated model

The sewer system has been simplified into a network of 48 sub-basins for the use of Kosim\(^3\). This simplification is based on uniformity with respect to both land and water use and geometric characteristics (slope, diameter, etc.). The definition of a maximum discharge at the outlet of the sub-basins accounts for the activation of internal storage capacity resulting from bottlenecks and backwater effects in a simplified way. This and other Kosim parameters are obtained from a hydrodynamic analysis with a detailed sewer model\(^4\). The variables \(\text{BOD}_{\text{particulate}}, \text{BOD}_{\text{dissolved}}, \text{SS}\) and ammonium are calculated by the model. The DO concentration of the overflow water is initially set to 5 mg/l, the fast BOD component amounts to 90\% of the total BOD concentration, the fast organic nitrogen component is considered to be 75\% of the ammonium concentration and a zero value is accepted for the nitrate concentration.

The behaviour of the wastewater treatment plant is modelled in a simplified way within the sewer quality model Kosim as well. Sedimentation in the rain tank is incorporated by the definition of settlement efficiency factors, while constant reduction coefficients are used to account for the biological treatment. The average DO concentration of the WWTP-effluent is found to be 7.5 mg/l from sample analysis data. All BOD and organic nitrogen is considered to be of the slow fraction. The organic nitrogen is calculated as 2.5 times the ammonium concentration, while the nitrate is initially taken as 5 times the ammonium concentration of the WWTP-effluent.

The river stretch considered in this study starts at the lower end of the river Molenbeek, upstream of overflow 1529.2, and has its lower boundary in the river Zwalm at Rozebeke, about 5 km downstream (Figure 1). The tributaries joining the river stretch from upstream to downstream are the rivers Dorenbosbeek, Zegelaarbeek (sub 123), Marebeek (sub 45), Dorrebeek (sub 678) and a smaller creek given the identification name sub 9&10. The stretch receives overflow water from the overflow structures 1529.2 and 85.2 as well as a discharge from the wastewater treatment plant at Brakel. A schematic representation of the river stretch is presented in figure 2. The stretch is divided into 114 elements with an average length of 50 m each. The number of elements between the lateral inputs is indicated in the figure. The tributary flows and pollutants are calculated with Desim, which is a mathematical model derived from Kosim. Changes to the program, such as the inclusion of a delayed runoff from infiltration water from unpaved areas, allows for simulation of larger catchments with an important natural flow. Diffuse pollution is accounted for using Desim as well. Desim calculates the BOD, SS and ammonium concentrations. The dissolved oxygen concentration is obtained through a curve fitting procedure with data from the Flemish Environmental Agency (i.e. VMM\(^5\)) in one of the tributaries. Again, the organic nitrogen concentration is taken to be equal to the ammonium concentration, while its fast component amounts to 75\% of the totality. 90\% of the total BOD is classified under the fast fraction. The nitrate concentrations from agriculture are calculated from data collected by the Institute for Chemical Research (ISO). Finally, the water temperatures are also determined based on
VMM measurement data through curve fitting. The river model used for the calculation of river flows and pollutants is Isis. The water quality processes considered in this study are the decay of organic material, reaeration, the nitrification processes of ammonia and mud sedimentation/erosion phenomena.

4 Calibration and verification of the model

4.1 Measurement data

Rain gauges are spread all over the catchment, but continuous registration is only available at the overflow site at Brakel. Flow was continuously measured in the sewer during the month of November 1997. The level in the overflow chamber is measured ultrasonically. A theoretical flow relationship for the weir crest is used to calculate the overflow discharges. Two samplers are provided to sample the overflow water and the water in the sewer during rain events for a period of 2 hours (12 samples). The following parameters are determined: BOD, SS, NH₄-N and Cl⁻. Only two events are available for the calibration of the sewer model.

About 5 measurements are carried out with respect to the sediment depth in the sewer pipe upstream and downstream of the overflow.

Both influent and effluent measurement data from the VMM of the wastewater treatment plant on a daily basis for about 30 days in 1997 and 1998 are used to verify the WWTP volumes and treatment efficiencies.

River flows are calculated from continuous level data from level gauges at Michelbeke (1991-1998) and at Brakel (1997-1998). The data available for the adjustment of the Desim quality parameters with respect to the tributaries are VMM monthly concentration values at the lower end of the Dorenbosbeek catchment. About 44 values (1991-1996) are useable with respect to BOD and ammonium, while 4 values only (1996) are registered regarding SS. The boundary conditions of the upper part of the model are supplied through the Desim model of the Molenbeek catchment. It was decided to reduce the model until Michelbeke in order to save simulation time. Level data for 1997-1998 at that location is available to be used as the lower boundary conditions of the model. The data finally used for the calibration process of the quality river model are on one hand analysis data gathered for the simulation of the overflow loads, i.e. sampling data upstream and downstream of the structure for 2 events. On the other hand, a measurement campaign during the month of November 1998 resulted in information allowing for adjustments with respect to the variables DO, NH₄-N, NO₃-N and water temperature. The data used for the verification process of the Isis quality model are the following:

- sample results upstream and downstream of the overflow and upstream of the WWTP during 1996-1998 (19 values) for the variables BOD, DO, NH₄⁺, NO₂⁻, NO₃⁻, SS and water temperature
- sample results at Michelbeke during 1995-1996 (18 values) for the variables BOD, DO, NH₄⁺, NO₂⁻, NO₃⁻, SS and water temperature
4.2 The sewer network

4.2.1 Quantity
The Kosim flow model is calibrated against a hydrodynamic model for an average year (i.e. 1985) by tuning the Kosim through flows in the system. The hydrodynamic flow model was calibrated on the basis of the measured flows in the sewer network. A runoff coefficient of 90% and a depression storage of 2mm were hereby found. These parameter values are used within the calibrated Kosim model that is verified with the help of the experimental overflow data. To this purpose, a simulation is performed over a period of 9 months in 1997-1998. The first graph in figure 3 represents the simulation result for the overflow discharge for one of the overflow events.

4.2.2 Quality
The washoff parameters of the Kosim quality model, i.e. constant washoff pollutant concentrations, are obtained by calibration against the overflow loads for one of the two events. Values for maximum settleable loads in the sewer are adapted to represent particulate fractions in a better way and to include the presence of pollutants trapped by the sediment layer. The verification result for ammonium concentrations for instance in the sewer system during the second rain event is represented in the second graph of figure 3. The washoff concentrations found are 11mg/l, 100mg/l and 3mg/l for BOD, SS and ammonium respectively, which is in accordance to values found in literature.

4.3 The wastewater treatment plant

The calculated influent volumes are verified by comparison with the measured volumes. A fair result is found accounting for the missing data in the rainfall series. It should be noted that more and complete data sets and a higher measurement frequency are needed to draw more precise conclusions.
The influent and effluent data are also used to determine the treatment efficiency of the water that receives biological treatment \((Q \leq 2.5 \text{ DW}F_{14})\). Efficiencies of 93%, 86% and 87% are found for BOD, SS and \(\text{NH}_4^+\) respectively. The efficiencies found out of the calculated influent concentrations and the measured effluent concentrations amount to 96%, 84% and 92% respectively, meaning that the calculated influent concentrations are well estimated by the model. The latter efficiencies are therefore used within the system.

4.4 The river environment

4.4.1 Quantity
Both the Desim and Isis flow models are calibrated simultaneously with the discharges of 1994 and verified for 1997-1998. The rain series used are those from Ukkel (Brussels) in 1994 (Royal Meteorological Institute) and Brakel for 1997-1998.

4.4.2 Quality
Initially, the Kosim washoff pollutant concentrations as described in paragraph 4.2.2 are used in the Desim models for the tributaries and the upstream boundary of the integrated system. These values are adjusted using the measurement data from paragraph 4.1 to obtain 30mg/l, 500mg/l and 1mg/l for BOD, SS and ammonium respectively. These values lie in the ranges found by Jolánkai. The verification procedure is based on a statistical analysis, i.e. the determination of average, median, 90 percentile and 10 percentile values for the calculated output series (for the year 1994) and the observed values. Literature values are used for the wastewater pollutant concentrations as no dry weather data is available. The parameter values found for the Dorenbosbeek catchment are passed on to the other tributary models.

The BOD, SS and \(\text{NH}_4\)-N concentrations of the river model are calibrated against the 2 available rain events, while \(\text{NO}_3\)-N, DO and water temperature are adjusted using sampling data of the month of November 1998. The model is found to be insensitive to a change of decay rates. An explanation is found in the high minimum velocities of the river (0.3-0.5 m/s) and the short trajectory of the pollutants (2.5 km), resulting in relatively short residence times (1-2 hrs). It is thought that the boundary conditions especially are a source of errors. The following had to be adapted in order to calibrate the river quality model:
- the SS and BOD concentrations of the Desim models are increased with a factor 3 and decreased with a factor 2 respectively
- the nitrate content for the month of November is dropped from 7.1 mg/l to 5.1mg/l for the Molenbeek and to 3.1 mg/l for the Dorenbosbeek; no further changes are proposed as no measurements are available during other months
- the nitrate concentration of the WWTP-effluent is set to the ammonium concentration
Calibration results are presented in figure 4 for BOD upstream of the overflow for one rain event and for DO downstream of the WWTP during a period of 10 days in November 1998. Verification is again performed on the basis of a statistical analysis of simulation output (of the year 1994) and the measurement data (see paragraph 4.1).

5 Discussion

5.1 Calibration results

A good sewer flow model can be obtained when attention is paid to a good quality of flow measurements in the sewer system and when the spatial distribution of rainfall within a catchment is accounted for. The absence of dry weather data hinders the calibration of the sewer quality model in particular. Additional points of difficulty are formed by the limited amount of good quality measured rain events (2 events in this study) and the simplification of the representation of erosion/sedimentation processes in Kosim. The advantage of a simple model is the low degree of detail of the measurement needed, however, the availability of enough data is imperative. The quality model cannot be calibrated against hydrodynamic models at the time being because of a questioned accuracy of the latter with respect to quality modelling.

A good river flow model is built despite a slight difference in the verification results which can be explained by the use of rain series from different rain gauges (Brussels-Brakel) during the calibration and verification process. The Desim quality model is calibrated roughly based on statistical analysis of results and measurements. The scarcity of experimental data did not prevent the river quality model to be well calibrated. However, automatic registration over different periods throughout the year is necessary, not only for a good estimation
of the boundary conditions. Automatic measurement stations are actually set up in the river to overcome this problem. The short measurement duration (2hrs for samplers or hand samples) is found to be problematic for sewer model calibration as well.

5.2 Practical aspects of integrated modelling

Integrated models can get complex because of the amount of elements involved, i.e. sewer system, river environment and WWTP. The use of simple and fast sub-models is therefore advised in order to keep an overall clear view of the situation and to allow for continuous simulations. Kosim is found to be appropriate to this purpose. It is questioned whether inclusion of quality processes within the model for the river considered in this study was necessary seen its high slope\textsuperscript{10}.

The simulation time is highly influenced by the river model. About 2 to 6 hours are needed for the simulation of a 1-year flow (pentiumII233-64RAM) and 40 hours are necessary with respect to the quality! Sewer flow simulation with a hydrodynamic model takes 40 hours as well. Integrated modelling with complex models is a time consuming activity. The use of commercial models leads to an increase of the simulation time due to space problems (large output files) and difficulties to process large amounts of data. Inflexibility is probably the most important disadvantage of commercial simulation models.

6 Conclusions

A fairly good calibrated integrated model is obtained and will be used to assess the impact of combined sewer overflows and to limit this impact by the use of different operating scenarios within the sewer. To this purpose, a move will be made towards the ecological interpretation of integrated model output\textsuperscript{11}.

7 Acknowledgement

Most of the experimental data used for this study was collected within the framework of the research projects G.0102.97 of the National Fund for Scientific Research and VMM-AMINAL/OVERST-F2/95 (and F3/96) of the Flemish Government.

8 References


5. [http://www.vmm.be](http://www.vmm.be)


