On data requirements for calibration of integrated models for urban water systems

Jeroen Langeveld, Ingmar Nopens, Remy Schilperoort, Lorenzo Benedetti, Jeroen de Klein, Youri Amerlinck and Stefan Weijers

ABSTRACT

Modeling of integrated urban water systems (IUWS) has seen a rapid development in recent years. Models and software are available that describe the process dynamics in sewers, wastewater treatment plants (WWTPs), receiving water systems as well as at the interfaces between the submodels. Successful applications of integrated modeling are, however, relatively scarce. One of the reasons for this is the lack of high-quality monitoring data with the required spatial and temporal resolution and accuracy to calibrate and validate the integrated models, even though the state of the art of monitoring itself is no longer the limiting factor. This paper discusses the efforts to be able to meet the data requirements associated with integrated modeling and describes the methods applied to validate the monitoring data and to use submodels as software sensor to provide the necessary input for other submodels. The main conclusion of the paper is that state of the art monitoring is in principle sufficient to provide the data necessary to calibrate integrated models, but practical limitations resulting in incomplete data-sets hamper widespread application. In order to overcome these difficulties, redundancy of future monitoring networks should be increased and, at the same time, data handling (including data validation, mining and assimilation) should receive much more attention.

Key words | calibration, IUWS modeling, river water quality modeling, sewer modeling, WWTP modeling

INTRODUCTION

In the last decade, many water authorities gradually shifted their approach towards integrated urban water management, driven by the Water Framework Directive (WFD) (EU 2000) and supported by: (1) research advances in the interactions between the sewer system, wastewater treatment plant (WWTP) and receiving waters (Rauch & Harremoës 1996; Langeveld 2004); (2) research advances in the relation between ecological status and physical-chemical status of receiving waters (Struijs et al. 2011); and (3) the availability of software that allows using integrated models (Schütze et al. 2002; Butler & Schütze 2005; Vanrolleghem et al. 2005).

These integrated models, like any other model, need to be calibrated and validated to enhance their reliability and reduce uncertainties in the model output to a sufficient level, allowing system managers to decide upon improvement or control measures. In this respect, a level of uncertainty lower than the impact of the measures to decide upon is deemed sufficient.

Even though the state of the art of monitoring is no longer the limiting factor (Benedetti et al. in press; Olsson 2012), calibration of integrated models for urban water systems is not routinely applied in practice nor in science, although some examples are available (Blumensaat et al. 2009).

Calibration of integrated models requires monitoring data that comprise sufficient information about the processes accounted for in the model. Ideally, this information can be obtained by monitoring the input for the integrated model (typically precipitation) and its output, e.g. concentration levels of dissolved oxygen (DO) and ammonia in the receiving waters (Figure 1). However, due to the limited parameter identifiability of a complete
integrated model, additional information is required at the level of the submodels for sewer, WWTP and river, each of which are facing their own issues related to identifiability (Brun et al. 2001, 2002; Reichert & Vanrolleghem 2001; Kleidorfer et al. 2012). The main source for this additional information is monitoring data, with a sufficient temporal and spatial resolution for all relevant state variables of the subsystems shown in Figure 1, for a specific period in time. The monitoring data requirements can be derived from the model to be calibrated, or, in other words, the model can be used to design or optimize the monitoring network (Clemens 2001, 2002; Kleidorfer et al. 2009). In the literature, much attention has been spent on the model-based design of monitoring networks (e.g. Sin et al. 2005), focusing on duration of monitoring period, temporal and spatial resolution (including number and location of measuring sites), and type and accuracy of measurements. However, little attention has been paid to the required performance of the monitoring networks. Recent research (Schilperoort 2011) has shown that the data availability of a monitoring network is typically significantly less than 100%, meaning that the data for any monitoring network will be incomplete and imperfect to a certain extent. Consequently, the performance of the monitoring network could have a significant impact on the data availability (both quantity and quality) and thus on the success of the calibration of the integrated model.

This paper discusses the efforts to meet the data requirements associated with integrated modeling and describes the methods applied to validate the monitoring data as well as to use submodels as software sensor to provide the necessary input for other submodels. This is illustrated by means of the case of the integrated urban water system of the Dommel River.

MATERIAL AND METHODS

System description: the Dommel River integrated urban water system

The Dommel is a relatively small and sensitive river flowing through the city of Eindhoven (The Netherlands) from the Belgian border (south) into the river Meuse (north), receiving discharges from the 750,000 person equivalent WWTP of Eindhoven and from over 200 combined sewer overflows (CSOs) in 10 municipalities (see Figure 2). In summer time, the WWTP effluent equals the base flow of 1.5 m$^3$/s of the Dommel River just upstream of the WWTP. The Dommel River does not yet meet the requirements of the European Union WFD. The water quality issues to be addressed are DO depletion, ammonia peaks and seasonal average nutrient concentration levels (Weijers et al. 2012). Benedetti et al. (2012) describe the set of measures required for compliance with the WFD and the methodology applied to derive them as developed in the KALLISTO project.

Monitoring network

In 2006 a monitoring network in the sewer, WWTP and river was set up and later updated and extended to be able
to deliver the information required to understand and model the integrated system. The monitoring network includes: (1) rain gauges, rain radar, flow and water level sensors in the contributing sewer systems; (2) ultraviolet/visible (UV/VIS) and ammonium sensors at the inlet of the WWTP; nitrate, ammonium, phosphate and oxygen sensors in the reactors of the WWTP; and (3) flow, ammonium and DO sensors in the Dommel River (Table 1).

The monitoring data have been validated prior to data analysis. The data validation involved checks on completeness, minimum–maximum and step trends (Bertrand-Krajewski & Muste 2008; Schilperoort et al. 2008).

Data validation

An assessment of the monitoring data over the period 2007–2009 (Schilperoort 2011) showed that the availability and quality of monitoring data ranges between 0 and 99.9% (Table 2). The data availability (percentage of maximum number of data points) is on average 85%, indicating that 15% of the potential data are lost due to communication problems or malfunctioning sensors. The availability of good data (not rejected during data validation) is significantly less. In addition, sensors typically do not fail at the same time (Figure 3). As a consequence, there are hardly any periods where all sensors in the network simultaneously provide reliable data, which should ideally be the case for proper model calibration as well as to provide good quality input to the model.

Model development

The integrated model was developed using the following approach.

- Creation of submodels:
  - Sewer: a full hydrodynamic model was made using InfoWorks (www.innovyze.com), comprising 21,955 nodes, 24,863 conduits, 108 weirs and 39 pumps.
Table 1 | Overview of the type of sensors used for integrated modeling along with their period of operation, monitoring frequency and specific remarks

<table>
<thead>
<tr>
<th>Type of measurement</th>
<th>Availability (from-till)</th>
<th>Monitoring frequency</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>1951–now</td>
<td>1 h⁻¹</td>
<td>Rainfall measurement of the Royal Netherlands Meteorological Institute</td>
</tr>
<tr>
<td></td>
<td>2006–2009</td>
<td>5 min⁻¹</td>
<td>25 rain gauges of Waterboard de Dommel</td>
</tr>
<tr>
<td></td>
<td>2010–now</td>
<td>5 min⁻¹</td>
<td>8 rain gauges of Waterboard de Dommel and Municipality Eindhoven combined with rain radar</td>
</tr>
<tr>
<td>Water level</td>
<td>2006–now</td>
<td>1 min⁻¹</td>
<td>Water level sensors in all pumping stations and control structures of Figure 2</td>
</tr>
<tr>
<td></td>
<td>2010–now</td>
<td>1 min⁻¹</td>
<td>Water level at all 200 CSOs</td>
</tr>
<tr>
<td>Flow</td>
<td>2006–2009</td>
<td>1 min⁻¹</td>
<td>Flow monitoring at all pumping stations, control structures and Dommel River</td>
</tr>
<tr>
<td></td>
<td>2006–2009</td>
<td>1 min⁻¹</td>
<td>Flow sensors at connections of municipal sewers to transport/interceptor sewer</td>
</tr>
<tr>
<td>Water quality</td>
<td>2006–now</td>
<td>2 min⁻¹</td>
<td>UV/VIS at WWTP influent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 min⁻¹</td>
<td>NH₄ at WWTP influent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 min⁻¹</td>
<td>PO₄ at WWTP primary clarifier (PC) effluent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 min⁻¹</td>
<td>UV/VIS at WWTP primary clarifier effluent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 min⁻¹</td>
<td>NH₄, NO₃ and PO₄ at WWTP effluent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 min⁻¹</td>
<td>DO at WWTP aeration tank</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 min⁻¹</td>
<td>DO at 3 locations in Dommel River</td>
</tr>
<tr>
<td></td>
<td>2010–now</td>
<td>1 min⁻¹</td>
<td>DO at 6 locations in Dommel River</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 min⁻¹</td>
<td>NH₄ at 1 location in Dommel River</td>
</tr>
</tbody>
</table>

Table 2 | Results of validation of monitoring data in the period 2007–2009

<table>
<thead>
<tr>
<th>Period</th>
<th>Data availability (%) of maximum number of data points</th>
<th>Availability of good (not rejected) data (%) of maximum number of data points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation (25 rain gauges)</td>
<td>80.6</td>
<td>0</td>
</tr>
<tr>
<td>Flow sensors at connections to transport sewer (FlotTotes)</td>
<td>78.5</td>
<td>19.3</td>
</tr>
<tr>
<td>Flow sensors at pumping stations</td>
<td>88.7</td>
<td>85.1</td>
</tr>
<tr>
<td>Flow sensors at WWTP influent</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>UV/VIS at WWTP influent</td>
<td>90</td>
<td>67</td>
</tr>
<tr>
<td>UV/VIS at PC effluent</td>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td>NH₄ at WWTP influent</td>
<td>78</td>
<td>0</td>
</tr>
<tr>
<td>NH₄ at PC effluent</td>
<td>82</td>
<td>&lt;45</td>
</tr>
<tr>
<td>PO₄⁻ at PC effluent</td>
<td>82</td>
<td>&lt;9</td>
</tr>
<tr>
<td>Water level at WWTP influent</td>
<td>99.9</td>
<td>99.9</td>
</tr>
<tr>
<td>Water level at control structures</td>
<td>87.4</td>
<td>&lt;42</td>
</tr>
</tbody>
</table>

- River: a 1D hydraulic model of the river is made using Duflow (STOWA/MX.Systems 2004), schematizing the Dommel River in 70 sections, 10 structures and 34 discharge points, representing (clusters of) CSOs and the WWTP effluent.
- Calibration of submodels, using different approaches per submodel:
  - Sewer: ‘calibrated’ using a dedicated approach to detect database errors and model anomalies. This approach does not aim at a perfect fit per event by adjusting model parameters related to the hydrological rainfall-runoff model, such as initial loss and infiltration in semi-impervious areas, as determining these parameters requires much more information than contained in the available monitoring data and these parameters typically have a low transportability. The approach used comprises three steps:
    Step A. Engineering validation and check search for gross model mistakes.
    Step B. Calibration of dry weather flow (DWF). This calibration is based on selected dry days, where a dry day is defined as a day with less than 0.1 mm of precipitation in that day and the preceding day.
    Step C. Calibration of wet weather flow (WWF) and storm events.
  - WWTP: calibrated using the BIOMATH calibration protocol (Vanrolleghem et al. 2005) adopting the ‘good modeling practice’ approach (Rieger et al. 2012),
i.e. the practice of adjusting as little as possible the model parameters of the biokinetic model. Due to the use of flow-concentration correlations based on online measurements of total and soluble chemical oxygen demand and total suspended solids in the influent, almost no calibration was actually required for this model (Cierkens et al. 2012b).

- River: same calibration approach as for the WWTP in terms of adjusting as little as possible model parameters. The main adjustment has been the fractionation of pollutants.
- Simplifying sewer model: the hydrodynamic sewer model is very computationally demanding and therefore simplified by a tanks-in-series hydraulic model, while maintaining the functionality of control stations and transport sewers. The simplified model is ‘calibrated’ using the detailed model predictions by adjusting the throttle flow for catchments discharging under gravity.
- Integration of submodels into a single integrated model in one simulation platform (i.e. WEST).
- Validation of the integrated model.

**Model calibration and validation**

The validation of the integrated model was intended to be performed using the same data sets used to calibrate the submodels. However, the data validation revealed that the data set, comprising data from 2006 to 2011, did not contain periods with sufficient data available to calibrate all submodels simultaneously. In order to overcome this problem, the following approach was applied,

1. Calibration of the hydrodynamic sewer model using calibrated rainfall radar data (i.e. radar data calibrated on high-quality ground stations) for the year 2011 as model input and measured flows at pumping stations and influent works as well as water levels at CSO locations as the
calibration data set. This period was selected as the only one where calibrated rainfall radar data were available, as well as monitoring data at all CSO locations of the Dommel River monitoring network.

2. Calibration of the WWTP model using validated influent monitoring data (flow, concentration levels from UV/VIS and NH₄) from the period 2007–2008 as model input and process parameters (e.g., sludge production) and measured WWTP effluent concentrations as the calibration data set. This period was selected as it was the only period with sufficient availability of influent quality data.

3. Calibration of the river model for the period January to August 2010 as input. This period was selected as only for this period was sufficient monitoring data on DO in the river available. The river model requires WWTP effluent and CSO discharges as model input. Data on WWTP effluent are available for this period, but monitoring data on the CSO discharges were not. This issue was tackled using the calibrated hydrodynamic model as software sensor (Leonhardt et al. 2012).

4. Validation of the integrated model: the integrated model was calibrated for the period January to August 2010, using one rain gauge as input and measured DO concentrations in the river as the calibration data set.

RESULTS AND DISCUSSION

Calibration of the submodels

Table 3 shows the available monitoring data for the calibration of only the Eindhoven sewer model for reasons of clarity, as the total list of data sources used to calibrate the hydrodynamic sewer models of all 10 municipalities is too extensive to show here.

A first attempt was made to calibrate the sewer model of Eindhoven using the 2010 data. However, the monitoring data available in this period does not contain sufficient information to be able to calibrate the model. In contrast, the monitoring data of 2011 did have sufficient quality and coverage of events to be used to calibrate the model. This calibration process revealed amongst others a number of wrong invert levels of main pipes and wrong dimensions of culverts. The calibration only aimed at identifying systematic errors in the model performance, indicating errors in the underlying database, which were changed in the database only after confirmation from field observations by the sewer manager (another data source). Consequently, the transferability between events of the results of the calibration was high compared with a

Table 3 | Data sources used to calibrate the hydrodynamic model of the city of Eindhoven

<table>
<thead>
<tr>
<th>Type of data</th>
<th>Monitoring network</th>
<th>Data source</th>
<th>Availability (period/% of time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>Rain radar</td>
<td>C-band radar of the Royal Meteorological institute</td>
<td>Since 1 January 2011. Only 75% of data could be locally calibrated due to insufficient data from rain gauges 2006–2011, &gt;90% availability</td>
</tr>
<tr>
<td></td>
<td>3 local rain gauges</td>
<td>SCADA system, Municipality Eindhoven</td>
<td>2010–2011, 40% availability due to communication issues</td>
</tr>
<tr>
<td></td>
<td>5 rain gauges of Waterboard De Dommel</td>
<td>SCADA system, Waterboard De Dommel</td>
<td>2010–2011, 40% availability due to communication issues</td>
</tr>
<tr>
<td>Water level</td>
<td>30 level sensors at CSO locations of old network, measuring range 30 cm below CSO weir level to 70 cm above CSO weir level</td>
<td>SCADA system, Municipality Eindhoven</td>
<td>2006–January 2011, &lt;10% availability due to communication and low robustness</td>
</tr>
<tr>
<td></td>
<td>30 level sensors at CSO locations of new network: measuring range sewer invert level – street level</td>
<td>SCADA system, Waterboard De Dommel</td>
<td>Since January 2011, 85% availability</td>
</tr>
<tr>
<td></td>
<td>30 temporary level sensors at various locations in network – measuring range sewer invert level – street level</td>
<td>Data storage, city of Eindhoven</td>
<td>6 months in 2010</td>
</tr>
<tr>
<td></td>
<td>Water level at pumping stations – varying measuring range</td>
<td>SCADA system, Waterboard De Dommel</td>
<td>2006–2011, &gt;95% availability</td>
</tr>
<tr>
<td>Flow</td>
<td>Flow sensors at pumping stations</td>
<td>SCADA system, Waterboard De Dommel</td>
<td>2006–2011, &gt;95% availability</td>
</tr>
</tbody>
</table>

SCADA: supervisory control and data acquisition.
typical model calibration procedure where runoff parameters are tuned to mimic the system dynamics during a specific storm event.

As indicated before, the river model was calibrated for the period January to August 2010. However, no reliable monitoring data were available for the 200 CSOs for this period. In order to overcome this problem, the calibrated sewer model was used as software sensor to produce the required input for the receiving water model. For the input from the WWTP the available monitoring data of the WWTP effluent was used. The performance of the river model with respect to simulating DO can be seen in Figure 4, which shows that the dynamics during both dry and wet weather are captured adequately by the model. The only parameter adjusted in the calibration of the river model was the fractionation of the organics in CSO discharges, in order to be able to mimic the delayed oxygen consumption of organic material deposited in the river sediment bed during a storm event. The model does underestimate the diurnal variation in the river, which is due to DO production and consumption by algae and water plants. Another disturbing factor is the fluctuation in the actual DO concentration in the WWTP effluent during DWF, which is not adequately covered by the DO sensor in the WWTP effluent.

Validation of the integrated model

The validation of the integrated model was performed for the same period as for the river model, as this is the only period when sufficient data on the receiving water quality was available. The performance of the integrated model is acceptable for the events of August 16 and August 28, but the CSO event of August 24 was completely missed (Figure 5). A detailed analysis of model inputs and model dynamics revealed that this was due to the used rainfall input. The input for the river submodel shown in Figure 4 was based on model simulations with the full hydrodynamic model, using the available data from three rain gauges for the Eindhoven area. In the integrated model, the 2,000 ha sewer model of Eindhoven is simplified as one tank, and only one rain gauge (the most reliable) was used as input. This example demonstrates the relevance of balancing spatial simplification of sewer system characteristics with taking into account the impact of spatially distributed rainfall data.

CONCLUSIONS

Running simplified, or parsimonious, integrated urban water system models requires only a limited number of input data sources, typically precipitation and upstream river conditions.
Calibration of integrated urban water system models, however, requires a substantially larger data set. Large monitoring networks with many monitoring locations may be required for the process of model calibration. As data availability, even for dedicated monitoring networks, will typically not exceed 85%, and complete datasets during a specific period might only be available for much shorter time periods (in this case <25%), other sources of information need to be identified if it is not possible to extend the monitoring period or the monitoring network. Gathering of these other information sources could involve the use of monitoring data from other networks, monitoring data from other periods transformed into useful information by using models as software sensors, and the use of other types of data such as field observations. This was illustrated in this paper for the case of the Dommel River. It was highlighted that in this context the sufficient availability of spatial data is a prerequisite for good model performance.

An additional option is to design monitoring networks with sufficient redundancy, as data losses are unavoidable and should not hamper the use of the monitoring data that are available. An integrated model could be used to determine the required level of redundancy in the network and used as a tool to design the monitoring network. This also holds for the required measurements at specific locations in order to predict certain events in the river.

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