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Online Monitoring of Combined Sewer Systems: Experiences and Application in Modeling

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The full understanding of flow dynamics and pollutant concentrations in combined sewer systems is an important issue in the management and design of these systems.

While detailed data of water levels and discharges is often available and is used in model calibration, water quality data in sufficient quality and detail is often lacking. Conventionally obtained samples (for example from automated samplers and lab analysis) cannot account for the full dynamics of pollutant concentrations encountered in sewer systems, such as the first flush occurrence in wet weather conditions. Moreover, the lack of field data is a critical aspect in modeling, with serious consequences for model calibration (Bertrand-Krajewski, 2007).

In Graz, Austria a sewer online monitoring station has been operated at a combined sewer overflow (CSO) at the outlet of an urban catchment area since 2002. Flow meters are installed in the inflow and the overflow channel of the CSO. A submersible ultraviolet-visible spectrometer probe measures continuously chemical oxygen demand (COD_{eq}), total organic carbon (TOC_{eq}) and total suspended solids (TSS_{eq}) concentrations, with intervals of 3 min during dry weather conditions and 1 min during wet weather conditions, directly in the overflow chamber (Gruber et al., 2005).

Two models of the catchment were set up in previous studies: an aggregated hydrological model in the SMUSI software and a detailed hydrodynamic model in SWMM 5.0. Both models have been coupled with an optimization algorithm based on evolutionary strategies, allowing auto-

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mated model calibration (Muschalla, 2008). The SMUSI model was calibrated against discharge and pollutant concentrations (COD_{eq}). The SWMM model, set up in late 2009, was calibrated against discharge so far.

This chapter describes the setup of the measurement station, the experiences obtained from its long term operation and the results obtained from the simulation models. The challenges in maintenance, operation and probe calibration are addressed and the limits of in situ sewer monitoring discussed. In addition the results of the discharge simulations from both models are compared, and the quality of the SMUSI model in COD_{eq} prediction is briefly discussed.

10.1 Methodology

In this section first the investigated urban catchment Graz West R05 as well as the sewer measurement station will be described. The SMUSI and SWMM 5 models are each briefly described and model calibration will be briefly discussed.

10.1.1 Urban Catchment Area *Graz West R05*

The Graz West R05 catchment is located in the western part of the city of Graz, the second largest city of Austria. The city of Graz lies in the south-eastern foothills of the Alps at 353 m altitude and is divided by the Mur River. The average annual rainfall depth is 830 mm.

The catchment was expanded between 2003 and 2006. It currently covers approximately 4.6 km^2 of which about 1.3 km^2 is impervious. Surface slopes range from 0.5% to 4% in the main part of the catchment, becoming steeper with up to 10% in the most western part.

A few smaller and two larger indirect dischargers are situated in the catchment. The population density is approximately 43 inhabitants/ha (about 19 500 inhabitants in total). The average dry weather flow, evaluated for 2009, is 40 L/s.

The sewer network is combined with some separate sewer connections. A variety of sewer profiles from circular pipes ranging from 150 mm diameter up to oval cross sections 1 300/1 950 and special cross sections, are in place. The total network length is currently 46.5 km. An in-sewer storage with a constant throttle runoff and a total volume of approximately 2 300 m^3 was installed in 2005. A combined sewer overflow (CSO) is situated at the catchment outlet. The overflow volume is spilled directly into the River Mur. Overflow starts at an inflow of about 500 L/s.

Detailed data on the catchment and the sewer system was obtained from cadastral maps, digital sewer map, aerial view photos, and land use maps provided courtesy of the municipality of Graz. An overview of the catchment is given in figure 10.1.

Precipitation data is available at high temporal resolution and is recorded by three rain gauges installed in the catchment.

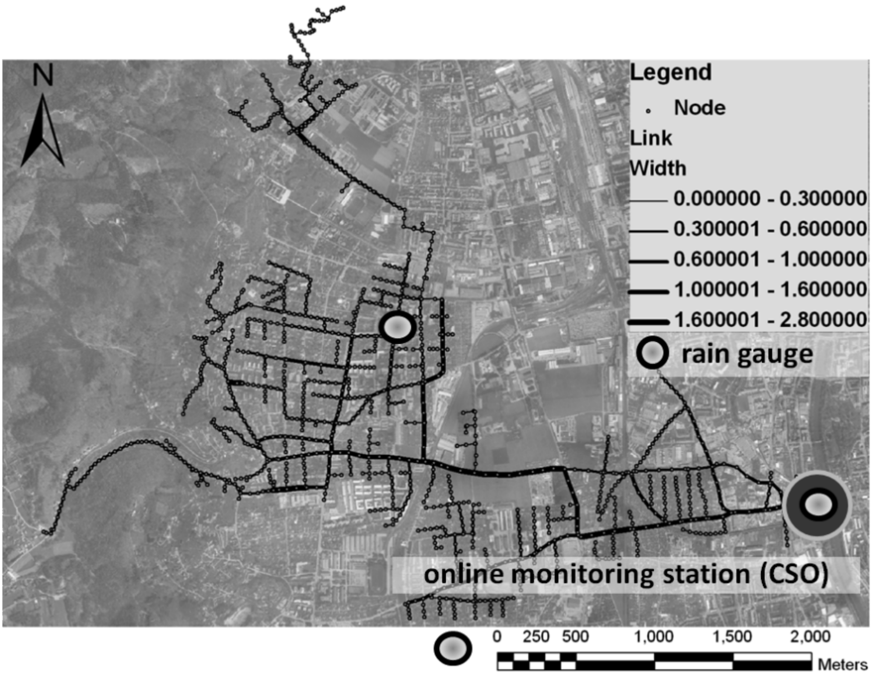

Figure 10.1 Catchment Graz West R05 with sewer map and aerial view photos.

10.1.2 Online Sewer Monitoring Station Graz Sewer R05

In 2002 an online sewer monitoring station was installed directly at the CSO R05 at the catchment outlet. It was set up under the auspices of the Austrian interuniversity research project named Innovative Technology for Integrated Water Quality Measurement IMW (BMLUW, 2005). It continuously measures hydraulic and water quality parameters. An overview of the layout and instrumentation of the station is given in Figure 10.2. An overview of the parameters measured, probes used and measurement periods is given in Table 10.1.

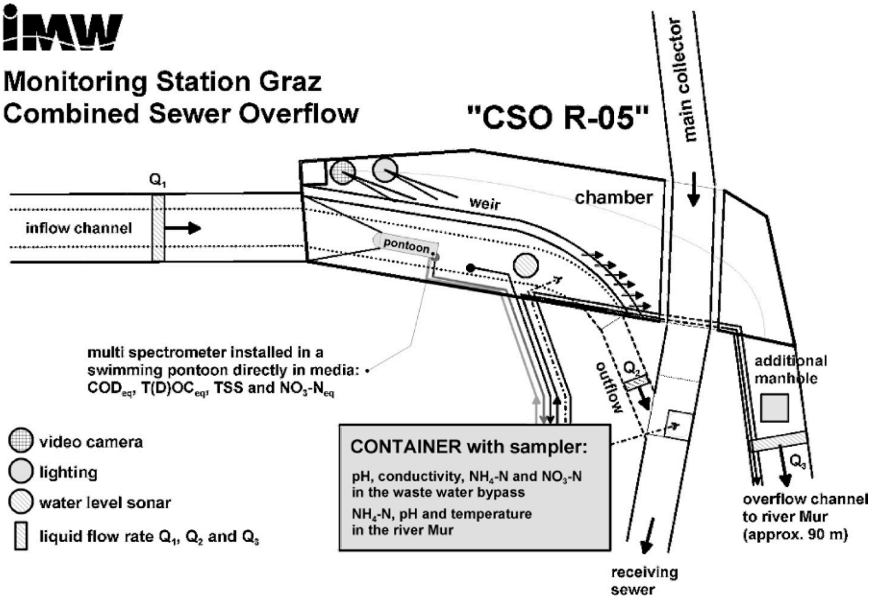

Figure 10.2 Layout and instrumentation of the sewer online monitoring station *Graz Sewer R05* (Gruber et al., 2004, modified).

Table 10.1 Measured parameters at Graz Sewer R05 monitoring station.

Parameter	Unit	Measurement method	Location	Period
HYDRAULICS				
Q inflow	L/s	radar	inflow channel	2002-ongoing
Q overflow	L/s	ultrasonic	overflow channel	2002-ongoing
Water level	m	ultrasonic	CSO chamber	2002-ongoing
WATER QUALITY				
COD_{eq}, TOC_{eq}, TSS_{eq}, $NO3_{eq}$	mg/L	UV/Vis spectrometer	floating pontoon	2002-ongoing
Conductivity	µS/cm	inductive	floating pontoon	2009-ongoing
NH4-N, NO3-N	mg/L	ISE probes	bypass	temporarily
Conductivity	µS/cm	conductive	bypass	temporarily
pH	pH	ISE probes	bypass	temporarily

Flow meters are installed in the inflow and in the overflow channel. An additional ultrasonic probe to measure the water level is installed directly in the overflow chamber. Water quality measurements are provided by a UV/VIS spectrometer probe installed directly in the overflow chamber in a floating pontoon. A bypass was operated in irregular intervals for additional water quality measurements. The bypass is situated in the measurement container (see Figure 10.2 above); the sampling hose is attached directly to the pontoon. In addition an automated sampler is installed that allows the drawing of reference water quality samples for probe calibration.

In dry weather conditions all data is logged with a standard interval of 3 min. In the case of stormwater, flow data is logged more frequently with the smallest attainable interval of 1 min. The change of the interval is triggered by the water level in the CSO chamber. The flow meters and water quality probes are connected to an industrial PC suitable for exterior installation. The PC controls the monitoring station and manages intermediate data storage. All sensors are directly linked to the station PC either via bus interfaces or via analogue inputs (4mA to 20 mA). A camera is installed inside the overflow chamber allowing a remote live view of the station. The camera is triggered by the CSO chamber water level to automatically record in case of storm events. Figure 10.3 shows a picture from the overflow chamber with the installed floating pontoon (dry weather conditions).

Figure 10.3 View of the overflow chamber and floating pontoon (remote shot from the installed camera, 2010 02 02).

Further details on the measurement station are given in Gruber et al. (2004) and Gruber et al. (2006).

UV/VIS spectrometer probe

The following paragraph briefly describes the UV/VIS spectrometer probe. Hochedlinger (2005) provides a more detailed description of all probes used.

The installed probe is a 5 mm spectro::lyser from the company s::can. It measures the light attenuation (absorption and scattering) in the ultra-violet and visible range between 200 nm and 750 nm. Based on the measured attenuation in different wavelength ranges, equivalent concentrations can be calculated for organic matter, as chemical oxygen demand (COD_{eq}) and total organic carbon (TOC_{eq}); total suspended solids (TSS_{eq}); and nitrate ($NO_{3,eq}$).

The probe is explosion proof allowing it to be used directly in the sewer system. Therefore it requires, apart from probe calibration, no sampling, no sample preparation, and no reagents. The spectrometer is equipped with an auto-cleaning system using pressurized air (Langergraber et al., 2003).

A global calibration for typical municipal wastewater is provided as default by the company. The site specific wastewater composition (wastewater *matrix* in the following) impacts on the water quality parameters derived from the absorption spectrum. The importance of local probe calibration has been highlighted in several studies, including Rieger et al. (2006), Gruber et al. (2006) and Torres and Bertrand-Krajewski (2008).

Winkler et al. (2008) discussed the uncertainties in UV/VIS measurements based on laboratory measurements for raw wastewater samples and concluded that the device is comparably robust if the matrix specific relationship between measured absorption and target parameter concentration is determined by a suitable correlation model.

10.1.3 SMUSI Catchment Model

SMUSI is a deterministic hydrological rainfall-runoff and stormwater quality simulation software tool developed at Technische Universität Darmstadt. In this study a version of SMUSI 5.0 (Muschalla et al., 2006) was used. The processes simulated include runoff formation and concentration from pervious and impervious areas; superposition of dry weather flow, imported water and storm water runoff in collecting pipes and structures; and translation and retention of hydrographs and pollutographs in the sewer system.

An aggregated model for the Graz West R05 catchment was set up in SMUSI by Schneider (2007), reflecting the network structure in 2003, and it was adapted recently by Fuchsberger (2009) to include the current network structure. The sewer system was aggregated in the model as 57 subcatchments and 56 main sewer pipes. In the results, pollution concentration in the runoff is calculated based on three components:

- an hourly concentration pattern is defined for dry weather flow;
- as particles in stormwater essentially originate from the impervious surfaces of the catchment and the atmosphere (see e.g. Bertrand-Krajewski et al. 1993), imported water and surface runoff from pervious areas is considered unloaded; and
- in surface runoff from impervious areas the calculations are based on a surface accumulation and wash-off process.

Sedimentation and erosion processes in the sewer systems are not considered separately.

10.1.4 SWMM 5 Catchment Model

The SWMM model of the Graz West R05 catchment was set up in the simulation software tool SWMM 5.0 (Rossmann, 2007) by Veit (2009).

After a thorough data check the complete available digital sewer map and connected subcatchments were imported to SWMM. The connected subcatchments were supplied by the municipality of Graz as a GIS system, and the degree of imperviousness was determined by overlaying with an infrared picture.

The network as represented in the model, consists of 1 164 subcatchments, 1 364 nodes and 1 363 links in total. Figure 10.4 shows the model of the Graz West R05 catchment in SWMM 5.0.

Figure 10.4 Graz West R05 catchment as modeled in SWMM 5.0.

Water quality parameters have not previously been taken into account in the SWMM model.

10.1.5 Model Calibration

Both the SMUSI and the SWMM model can be coupled with an optimization algorithm based on evolutionary strategies. This coupling allows single- and multi-objective optimization by minimizing one or more objective functions. For multiple objectives the best performing model parameter sets are determined based on the concept of Pareto optimality (Deb, 2001). A description of the algorithm is given in Muschalla (2008).

Several studies were carried out to assess the performance of the algorithm for calibration of the SMUSI model for both hydraulics and storm water quality (Muschalla et al., 2008; Gamerith et al., 2009).

The SMUSI model representing the network status in 2003 was automatically calibrated against discharge and water quality for dry and wet weather conditions. Previously the expanded part was calibrated only against dry weather runoff, and model parameters were chosen to be similar to those from the calibrated part.

The SWMM model was calibrated manually against discharge in dry and wet weather conditions so far. An automated calibration with the optimization algorithm is currently in preparation.

10.2 Results and Discussions

This section first details the information obtained in long term monitoring and addresses the challenges encountered in operation as well as probe calibration and data management. Next, the results obtained with the SWMM 5 and the SMUSI models are presented and discussed. A final comment will be made on the results obtained with the SMUSI model in water quality modeling.

10.2.1 Experiences in Long Term Monitoring

Concerning the flow measurements, both the contactless radar gauge in the inflow channel and the bottom bound ultrasonic device in the overflow channel have been shown to be stable over the entire measurement period. The only issue was the physical measurement limits (see later). Experience so far shows that contactless gauges seem better adapted to sewers where near-bottom solids are expected (e.g. gravel) and bottom bound probes would risk being damaged.

Probe location

In sewer water quality measurement the choice of the sampling location is crucial to obtaining viable results (Bertrand-Krajewski et al., 2000).

The decision to install the UV/VIS sensor in a floating pontoon allows continuous measuring in the uppermost layer of water. As this layer reaches the overflow first, this measurement location seems appropriate to assess overflow concentration. Deducing concentrations over the cross section might not be valid as complete mixing needs to be assumed in that case.

Installing the probe directly in the sewer demands a robust installation that can withstand both the strong dynamic stresses due to hydraulics (flows can reach up to 10 m³/s at the measurement site Graz sewer R05) and the aggressive environment (e.g. corrosion problems, grease, clogging). As it is installed directly in the sewer, all instrumentation has to be explosion proofed. A comparison of the pros and cons of direct in-sewer and bypass installation is given in Gruber et al. (2006).

Besides these requirements, there are more practical issues that have to be taken into account: the availability of places to install a measurement container, connection to electricity, easy and permanent access to the sewer, protection from vandalism, and such. Often these requirements are the limiting factor for the choice of a suitable location.

In addition the installation itself is rather complex requiring cable ducts for data cables, and a supply of pressurized air connecting the sewer and the measurement container, which is usually located at ground level.

In 2009 a general overhaul of the UV/VIS probe was necessary: corrosion of the probe and a short-circuit caused by the data cable led to the loss of over one month's data.

Experiences from Operation: Clogging and Drift

As the floating pontoon is installed directly in the sewer it is subject to clogging. After major initial clogging problems, two measures were put in place: a steel baffle was placed in the dry weather channel to raise the minimum water level; and a piston driven cable winch was installed which could be activated remotely to lift the pontoon, allowing the removal of the clogging. These measures significantly reduced the requirement for maintenance on site. A schematic overview of the installation is given in Figure 10.5.

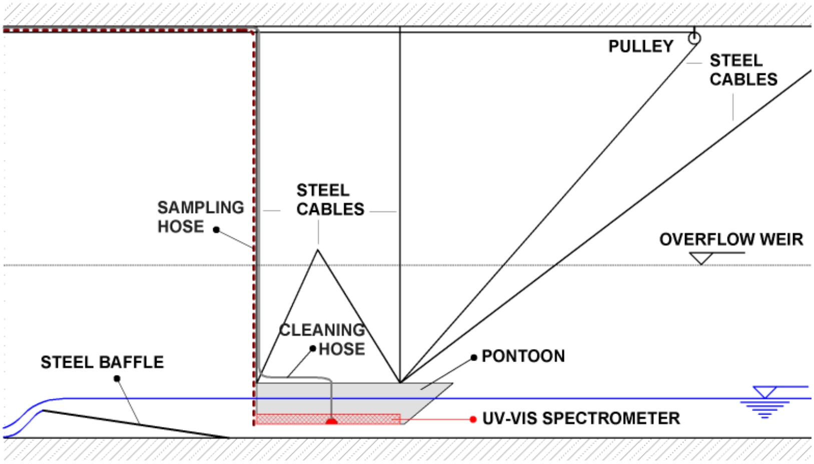

Figure 10.5 Schematic installation with steel baffle, steel cables, cleaning and sampling hose (Hochedlinger, 2005).

The 5 mm^2 measurement window of the UV/VIS probe is automatically cleaned by pressurized air after every fifth measurement. In July 2004 the cleaning system failed, which led to a drift in the absorption measurements due to the buildup of biofilm on the window. After repair and thorough manual cleaning, the re-activation of the cleaning system was forgotten for three further weeks, which resulted in the same drift behaviour. The effect of this omission, based on COD$_{eq}$ measurements, can be seen in Figure 10.6. The absolute difference before and after repair is about 550 mg/L COD$_{eq}$.

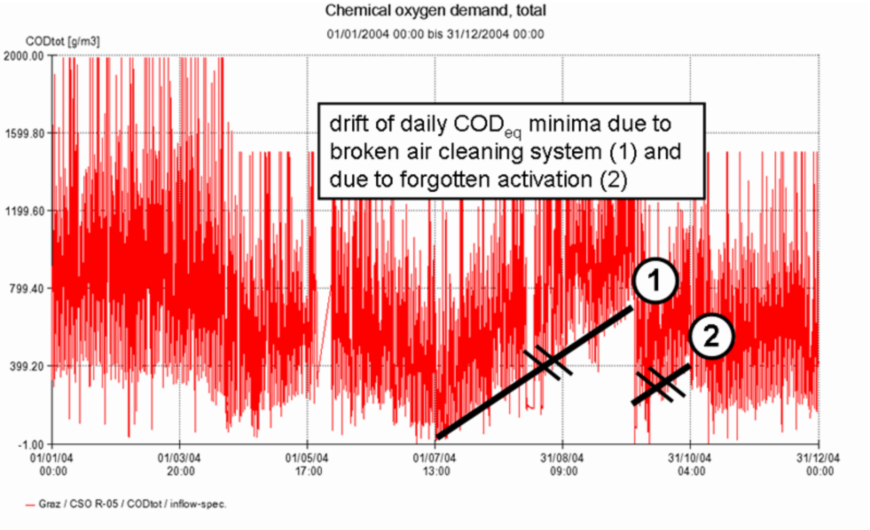

Figure 10.6 Drift in COD$_{eq}$ measurement due to broken cleaning system (Gruber et al., 2006).

Measurement limits

Since most of the sensors at the measurement station are connected to the PC by an analog connection (currents of 4 mA to 20 mA), measurement limits are defined by two sources:

- the physical measurement limit of the sensor itself; and
- the limits defined for the analog connection of the sensors to the PC (equivalent values for 4 mA and 20 mA).

Generally limits for the analog connection are defined as *reasonable* limits for each sensor, knowing that the bigger the span the less precise the results will be.

For the radar flow meter in the inflow channel, measurement limits are determined by the minimum required distance from the water level (physical limit) and the definition for the analog connection between 0 (4 mA) and 2 500 L/s (20 mA). The maximum of 2 500 L/s were chosen based on the dry weather calibration.

Additionally the flow meter internally stores all measured data digitally for about 10 days. Figure 10.7 shows the effect of the two limits for an extreme rainfall event in June 2008, where the internal storage of the flow meter was read out manually after the event.

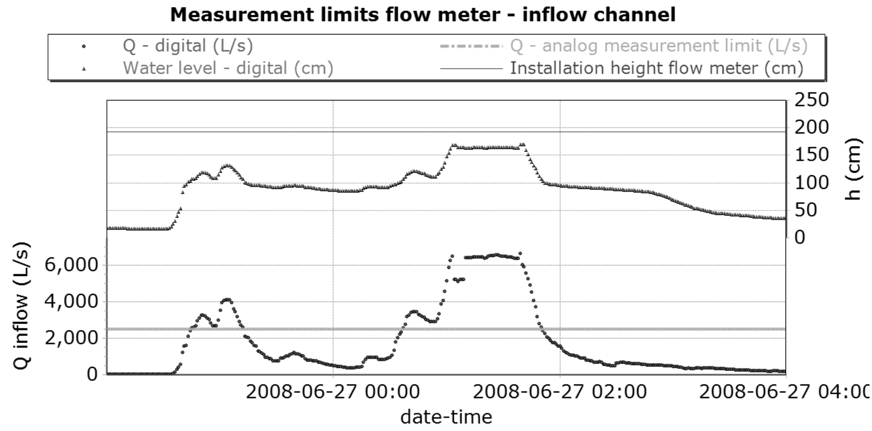

Figure 10.7 Analog and digital measurement limits, flow meter inflow channel.

The digital data from the internal storage of the flow meter (Q-digital) shows that the first peak of the event was recorded completely. The second peak surpassed the physical limit of the flow meter (minimum distance to water level). A maximum flow of about 6 000 L/s was measured. Due to the physical limit, no higher values can be recorded. In the data transmitted to the PC and eventually stored in the database, however, both peaks are cut off at the defined measurement limit of 2 500 L/s.

This shows the importance of setting measurement limits with care, as important data loss may be the consequence. In our case this situation was identified because of the model results for peak events and intensive data analysis. Currently an evaluation of the analog limits is under way; they will be adapted in near future.

Probe Calibration

The flow meter in the inflow channel was calibrated in dry weather conditions by Haas (2005). In wet weather conditions, meaningful calibration by tracer methods requires much effort and was not carried out. Calibration results showed that initially a wrong sewer cross section was provided for flow calculations, which led to biased results, especially in low flow.

Concerning the UV/VIS spectrometer probe, several sets of measurements in both dry and wet weather conditions were obtained for local probe calibration. Details on the dry weather calibration and the use of different regression methods are given in Hochedlinger et al. (2006). Currently a study is being carried out to evaluate the behavior in wet weather flow. Preliminary results lead us to assume that uncertainties for wet weather flow are significantly higher than for dry weather conditions due to the changes in the wastewater matrix during storm events. Similar behavior has been observed by Stumwöhrer et al. (2003) based on UV measurements of COD_{eq} concentrations during storm events.

Maintenance and Logging

Thorough maintenance by well trained personal proved to be one activity critical to the proper functioning of the measurement station. Experience so far has shown that the spectrometer and the bottom of the sewer should be cleaned manually by means of a high pressure cleaner every two weeks. This means that personnel have to be trained for in-sewer work. Additionally the state of the floating pontoon is checked visually through the remote camera after every event. Thus problems are quickly identified and possible downtime is reduced.

In order to use the recorded data for statistical analysis or modeling, the logging of all maintenance activity proved to be crucial. So far this has been done using a digital maintenance log directly on site.

Data Management

Experience has shown that an effective means of storing and accessing the large amount of data produced is required. The database developed for the first project phase reached its capacity limits in 2007. Access to data proved to be costly in terms of computation time. Currently a new database is under development based on the netCDF file format and an Open Source server, a solution which has given very promising results so far.

10.2.2. Comparison of SMUSI and SWMM 5 Results (Hydraulics)

In this subsection the results obtained with the SMUSI and the SWMM 5 models are compared. The most recent version of each model was used, representing the current network status as of 2009.

The models were validated using data from January to June, 2009. Events were classified based on their peak flows as small, medium and large (see

Table 10.2). Overflow at the CSO starts at inflows between 500 L/s and 600 L/s.

Table 10.2 Classification of events and occurrences Jan. 2009–Jul. 2009.

	Small event	Medium event	Large event
Ma10. peak flow (L/s)	500	2 000	>2 000L/s
No of events Jan 09–Jul 09	4	19	11

Based on a visual analysis for obvious measurement errors (in either rainfall or flow measurement), results from the SWMM model were evaluated for 12 chosen events for volume error and the Nash-Sutcliffe efficiency coefficient E_Q (Nash and Sutcliffe, 1970). Events with peak flow higher than 2 500 L/s could not be evaluated due to missing measurement data. The results are presented in Table 10.3. With one exception volume errors are in the range ±20%. For six of the twelve events $E_Q > 0.8$ is reached and the minimum E_Q is at 0.27.

Table 10.3 Analytical analysis of SWMM results (Veit, 2009, modified).

Date	category	peak flow		E_Q	Volume error
(D M Y)		measured (L/s)	simulated (L/s)		(%)
02/03 Dec 08	small	400	450	0.85	+19
11/12 Dec 08	medium	550	550	0.86	+10
16/17 Dec 08	small	250	200	0.27	+18
20/21 Dec 08	small	200	200	0.83	+13
21/22 Jan 09	medium	550	550	0.94	-2
27/28 Jan 09	medium	700	650	0.53	-11
06 Mar 09	medium	620	620	0.91	-11
19/20 Apr 09	small	300	340	0.57	+26
29/30 Apr 09	large	2 200	2 400	0.82	+7
27 May 09	medium	1 000	1 170	0.77	-5
23 Jun 09	medium	840	840	0.65	-10
01 Jul 09	medium	1 000	1 100	0.37	+10

In the following, figures for the results obtained by both SMUSI and SWMM for one event of each class are presented. In the figures, discharge (L/s) figures are on the left axis and precipitation intensity (mm/5 min) on the right axis. Measured values are represented by the dotted line, SWMM results by the continuous line and SMUSI results by the dashed line. Note that the scales for precipitation intensity as well as runoff vary for the different events, in order to make the figures legible.

Generally, satisfactory results are obtained for small and medium events with both the SMUSI model and the SWMM 5 model (see Figures 10.8 and

10.9). The dynamics of the runoff could be reproduced. Start and end of the events are mostly well fit. The SMUSI model shows a higher fluctuation in the calculated runoff, while SWMM gives a smoother response. The measured data is in between the two. Most likely this difference is linked to the parameters of the subcatchments. We expect this to be resolved after further calibration work.

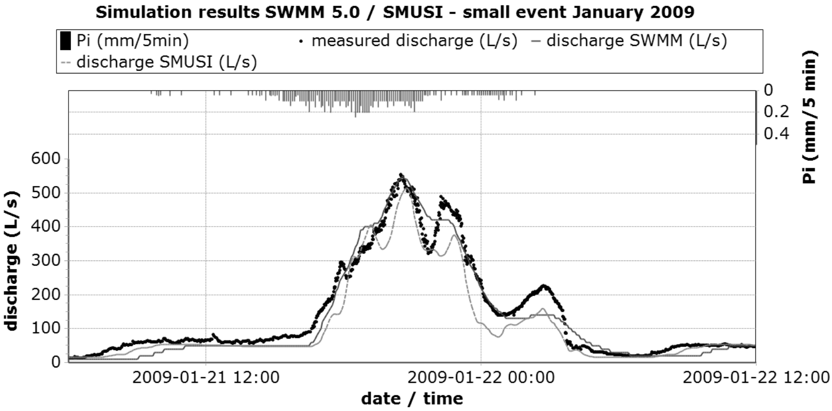

Figure 10.8 SMUSI and SWMM 5 results for a small event in January 2009 (hydraulics).

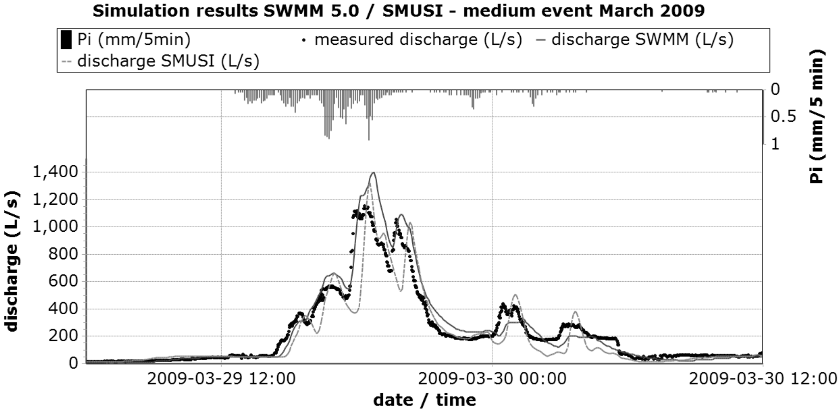

Figure 10.9 SMUSI and SWMM 5 results for a medium event in March 2009 (hydraulics).

The results for large rainfall events (Figure 10.10) show the problem stated above concerning the measurement limit. The runoff peaks resulting from the SMUSI and SWMM models are at 6 200 and 7 000 L/s respectively. As the measurement is limited to 2 500 L/s no statement about the quality of the models can be made for these large events. However, the second runoff peak of about 2 200 L/s is rather well fitted. This is congruent with the interpretation that infiltration parameters are chosen in a realistic range to reproduce the measured runoff.

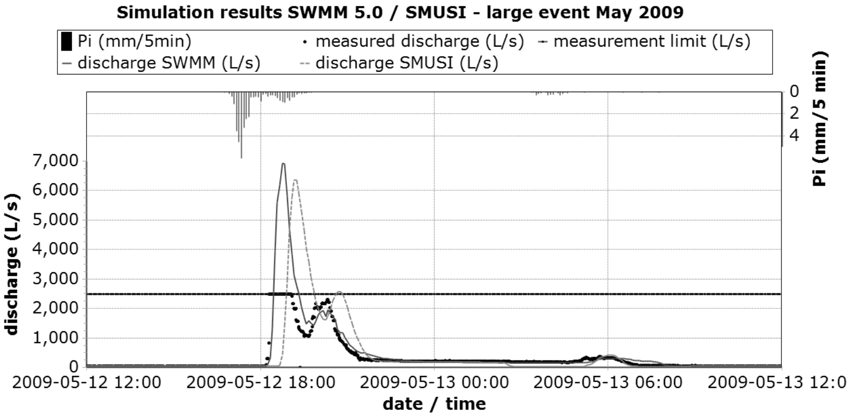

Figure 10.10 SMUSI and SWMM 5 results for a large event in May 2009 (hydraulics).

There is a time shift in the SMUSI results, which becomes slightly larger for large events. The reason for this is not yet determined.

Currently the in-sewer storage is reproduced better by the SWMM model. This was to be expected as SMUSI uses a static backwater approach for storage units and cannot take into account the full dynamics in the storage volume. This, however, could be addressed in further calibration work.

10.2.3. Water Quality Modeling in SMUSI

For water quality modeling the SMUSI model with the 2003 network has been used to date. In this chapter the results are only briefly discussed. Detailed analyses of the results have already been presented in Muschalla et al. (2008) and in Gamerith et al. (2009). Generally, satisfactory results were obtained from the analysis of the 2003 and 2004 data.

Figure 10.11 shows measured and simulated COD_{eq} concentrations (right axis), measured and simulated inflow as well as precipitation intensity (left axis) for a period in November 2003. The dynamics in the COD concentrations can be reproduced by the model. However, the fluctuation in simulated concentrations is still high compared to the measured values.

In the near future the SMUSI model using the 2009 network will be calibrated against COD and TSS. In addition the quality approach of SWMM will be used and calibrated.

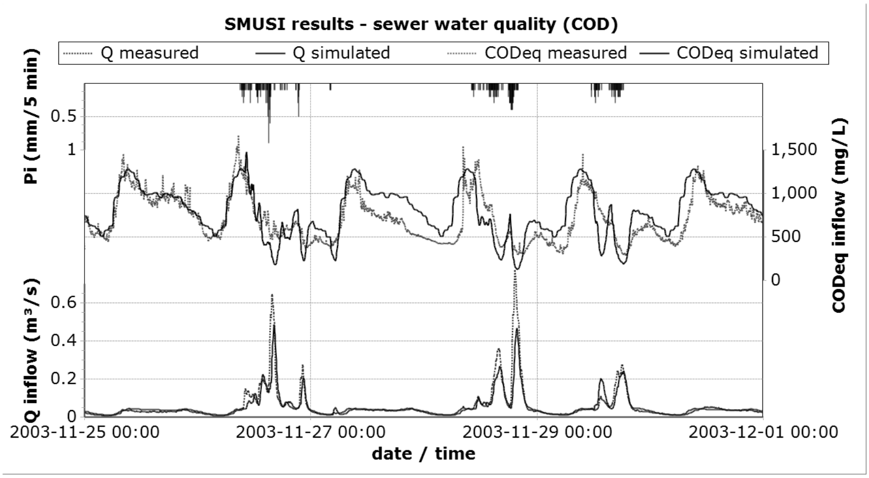

Figure 10.11 SMUSI results for COD concentrations, November 2003.

10.3 Conclusions

In this chapter we discuss our experiences in long term in-sewer online monitoring at a monitoring station in Graz, Austria and the application of the data in modeling. The measurement station has been continuously operated at a combined sewer overflow at the outlet of an urban catchment area since 2002. Flow data and water quality data are logged at an interval of 1 min by flow meters and a submersible UV/VIS spectrometer probe respectively.

The installation of the probes directly in the sewer system poses several challenges: choice of location, accessibility, robust installation withstanding the dynamic forces and corrosive environment, and the use of trained personal for regular maintenance.

Experiences over the last years showed that, after initial problems were overcome, comparable robust and reliable measurement results are obtained. However, permanent supervision and regular maintenance have to be ensured.

Probe calibration for quality measurements is still an issue, especially in wet weather conditions. While the accuracy of the obtained absolute values might be questionable, continuous measurements allow the inspection of the full dynamics of pollution concentrations in the system. This is not possible to the same extent with traditional sampling methods. Knowledge of the full dynamics can help in determining the system behavior as e.g. occurrence of first- or last flush effects or to identify rainfall and runoff characteristics with the highest impact on spilled pollution loads. This can help in the design of overflow and retention structures to optimize pollution reduction. In addition, such measurements are of special interest for water quality driven real time control of sewer system.

In addition the high data output makes demands for proper tools to manage (store and access) the recorded data. Currently a new server based Open Source solution is being under development for the measurement station.

Two models of the catchment were set up in previous studies: an aggregated hydrological model in the software SMUSI (Muschalla et. al., 2006) and recently a detailed hydrodynamic model in SWMM 5 (Rossmann, 2007). The SMUSI model was calibrated against discharge and pollutant concentrations (COD_{eq}). As the catchment was continuously expanded from 2004 to 2006, the SMUSI model had to be adapted to include the network as it was in 2009; the expanded part is not calibrated yet. The SWMM model, set up in late 2009, was calibrated manually against discharge so far.

A comparison showed that both models give satisfying results for hydraulics for small and medium events. An evaluation of large rainfall event was not possible due to the measurement limits in the flow measurement. Based on the model results, measurement limits have been redefined. The in-sewer storage is better represented with the SWMM model.

Future work will focus on the in-depth calibration of the two models representing the current network status. In addition, the effect of distributed rainfall will be addressed. Most interesting is the implementation of the pollution concentration approach in SWMM.

Acknowledgment

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