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Transport Sewer Model Calibration by Experimental Generation of Discrete Discharges from Individual CSO Structures

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Abstract: For the development of real-time control systems of integrated urban wastewater systems (IUWS) fitting a model to measurement data is an important task. Generally, model complexity conflicts with computational demand. The problem increases when multi-criteria optimization is carried out. Therefore, in the case of IUWS modeling hydrological approaches are case dependant alternatives to full hydrodynamic descriptions. The study presents the results of a unique flow time test in a new IUWS in Luxembourg, a predominantly combined sewer system. During this test dry weather flow (DWF) was stored in several combined sewage overflow tanks (CSOT) for a certain time and discharged to the downstream wastewater treatment plant (WWTP) in a particular temporal sequence to mimic combined sewage flow (CSF). Consequently, the analysis of the related inflow measurement at the WWTP allows for explicit flow time identification for each CSOT. For the integrated sewer network a non-linear hydrologic modeling approach is chosen as hydraulic description while pollution load modeling is based on a Lagrange based approach. Results show good matches for both model calibration and validation for a real rain event. During the non-linear hydrologic sewer model calibration the CSF turns out to be very sensitive to the number of tanks in series and the Manning roughness coefficient while the DWF modeling is rather insensitive to these parameters.

***Keywords**:* Advective pollution load modelling; combined sewer systems; integrated modelling; Lagrange; non-linear hydrologic modelling

1 INTRODUCTION

Real-time control (RTC) of integrated urban wastewater systems (IUWS) is on its way from research to implementation. Many research studies have shown its relative benefit as shown in Muschalla et al. [2009]. In order to study actual benefits the underlying integrated model must be calibrated. Thus, fitting the model to measurement data is an important task. On the other hand model complexity plays an important role when it comes to promoting integrated RTC as state of the art. Generally, model complexity conflicts with computational demand and Muschalla [2008] shows that the problem increases if optimization is required. When balancing performance and treatment costs the optimization within IUWS even becomes a multi-criteria problem. Therefore, Meirlaen et al. [2001] conclude that hydrologic modelling approaches are case dependant alternatives to hydrodynamic approaches. Hydrologic modelling approaches range from pure hydraulic translations as used by Fiorelli and Schutz [2009] to sophisticated non-linear approaches with partial linearization as introduced by Ostrowski [2002] or mechanistic surrogate models as used by Meirlaen et al. [2001]. The aim of this study is to present the results of a unique in situ test for the calibration of the transport sewer model as link between local catchment sewer networks and the wastewater treatment plant (WWTP) in IUWS modelling. Additionally, the use of a combined Lagrange based advective pollution load model – non-linear hydrologic model (NLHM) as an alternative to hydrodynamic approaches is discussed. The test is part of the calibration procedure of optimization studies on (i) linear combined sewer network models as described by Fiorelli and Schutz [2009] and (ii) on the integrated operation of wastewater systems with central treatment in rural regions as described by Regneri et al. [2010].

2 MODEL DESCRIPTION

2.1 Hydraulic model

The integrated model is set up with SIMBA®. Details on this MATLAB©/Simulink® based software bundle for wastewater treatment modelling are given in Ifak [2007]. Since computational effort plays a crucial role in multi-criteria optimization of integrated wastewater models a hydrologic approach is chosen for hydraulic flow routing within the sewer network sub-model. For such cases SIMBA® provides a hydrologic approach based on nonlinear cascade modelling with advective pollution load modelling based on a Lagrange approach. Since hydraulic systems are nonlinear, hydraulic modelling should be nonlinear too. Ostrowski [2003] demonstrates the uncertainties that accompany linear hydrological models. In order to combine accuracy and computational performance the nonlinear hydrological approach is chosen. Based on the Kalinin-Miljukov approach modified for pipe flow introduced by Euler [1983] the pipe is divided into n reference sections which define the structure of a retention cascade where the effluent of each tank forms the influent of the following tank (figure 1).

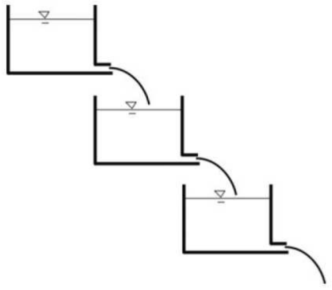

Figure 1 Retention cascade

In contrast to linear approaches hydraulics within each section are then derived from popular partial pipe filling diagrams where the nonlinear relation of water level h [m], flow cross-section A [m^2], velocity U [m/s] and discharge Q is described for a sufficient number of reference points. Here, velocity U [m/s] is calculated according to the Manning-Strickler equation (1) where r_{hy} is the hydraulic radius and I the slope of the pipe. Finally Q is the product of A and U (2).

$$U = \frac{1}{n_{Manning}} \cdot r_{hy}^{2/3} \cdot \sqrt{I} \qquad (1)$$

$$Q = A \cdot U \qquad (2)$$

Figure 2 shows the nonlinear relation between h, A, U and Q for a circular pipe of 1.0 m diameter, a slope of 0.01 and a Manning roughness coefficient of 0.013

(centrifugally spun concrete). More details on partial pipe filling diagrams are given in Hager [2010].

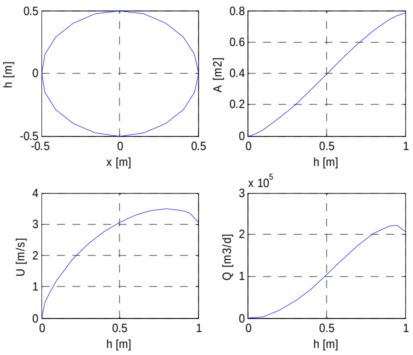

Figure 2 nonlinear relation h, A, U, Q

Results are compared to hydrodynamic modelling done with Infoworks CS®. Here flow routing is described by kinematic waves by solving the 1D “de Saint-Venant” equation (3) where g is gravity [m/s^2], x is the coordinate in flow direction [m], I_o is the bottom slope [-] and I_f is the energy slope [-]. Calibration is done according to the roughness coefficient based on the Colebrook-White equation (4) where λ is the drag coefficient [-], Re is the Reynolds number [-], k is the roughness coefficient [m] and d is the inner pipe diameter [m].

$$\frac{1}{g}\frac{\partial u}{\partial t}+\frac{u}{g}\frac{\partial z}{\partial x}+\frac{\partial h}{\partial x}=I_o-I_f \tag{3}$$

$$\frac{1}{\sqrt{\lambda}}=-2\cdot\log\left(\frac{2.51}{Re\cdot\sqrt{\lambda}}+\frac{k}{3.71\cdot d}\right) \tag{4}$$

Simple flow time calculations are done according to Prandtl-Colebrook for complete filling and an operational roughness coefficient k_b = 1.5 mm. Then flow times for partial filling are derived from partial pipe filling diagrams (see before). A description of the calculation is given in Hager [2010].

2.2 Pollution load model

The pollution load transport is described by an advective type Lagrange based approach. Details are given in Ifak [2007]. The core principle of this approach is the movement of discrete balance volumes along the flow axis. With these volumes it is possible to describe transport of matter without numerical dispersion. Balance volumes can be added or taken away at both ends of the queue. The approach considers dispersion of matter between neighbouring volumes by mass flow from volume i to i+1 according to equations (4) to (6) for fixed time steps T_0:

$$m_{i\rightarrow i+1,j}=J_{i\rightarrow i+1,j}A_{i/i+1} \tag{4}$$

$$C_{i,j}(k+1)=C_{i,j}(k)-\frac{m_{i\rightarrow i+1,j}}{V_i}T_0 \tag{5}$$

$$C_{i+1,j}(k+1)=C_{i+1,j}(k)+\frac{m_{i\rightarrow i+1,j}}{V_{i+1}}T_0 \tag{6}$$

Conversion processes can be considered through inclusion of equations in the form of Gujer matrices. However, mass balances from measurement campaigns at the catchments and the WWTP inlet show that degradation processes within the transport sewer network are negligible.

3 THE HAUTE-SÛRE WASTEWATER SYSTEM

The calibration was performed in a rural wastewater system situated around the Haute-Sûre drinking water reservoir in the North of Luxembourg. Regneri et al. [2010] give a detailed overview on the combined sewer system with central treatment at the WWTP Heiderscheidergrund. The overall system is currently under construction. At the moment it comprises eight villages with 3869 population equivalents (PE) and 80 ha of impervious catchment surface are connected to the sewer system. Eight CSOT located downstream of each village provide a total tank volume of 1600 m³. Four catchments are connected to the downstream transport network by pumps. The combined sewer transport network has a total length of 19.7 km with 4.1 km of pressure conduits. Figure 3 gives a rough impression of the current system.

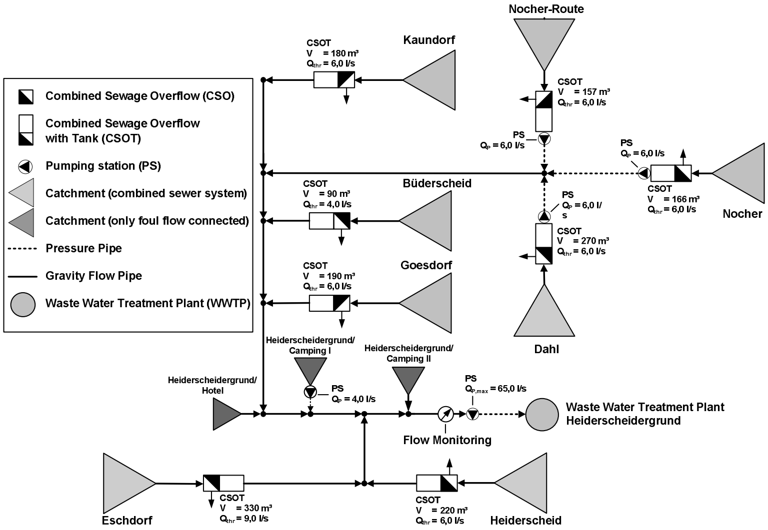

Figure 3 System overview

4 FLOW TIME TEST

The objectives of the presented flow time test (FTT) are on the one hand (i) the validation of the mean hydraulic transport times for simplified modelling according to the approach of Fiorelli and Schutz [2009] and on the other hand (ii) the calibration of the integrated sub-model of Regneri et al. [2010] for the transport sewer network situated in between the local catchments with their CSOT and the WWTP. The test was conducted on a dry weather day. During this test the DWF to each CSOT was stored for a certain period by simultaneously closing all throttles at a given time and discharging the throttled volumes in a particular temporal sequence according to their distances to the WWTP in order to mimic a CSF event. For operational reasons, the respective CSOT operation returns to normal control after the discharge of the bulk wastewater. The test provides a unique opportunity to measure flood waves mimicking CSF allocable to certain CSOT discharges which is under normal conditions not the case. For discharge control each CSOT is equipped with an inductive flow measurement device (IFMD). Consequently, the analysis of the related inflow measurement at the WWTP allows for explicit flow time identification for each CSOT. In order to remove temporal effects of pumping at the WWTP inlet, a mobile probe based on the cross-correlation method is installed a few meters upstream of the WWTP inlet. This additionally allows for validation of the inflowing volume.

5 RESULTS AND DISCUSSION

5.1 Hydraulic calibration

Figure 4 shows the flow rate monitored ~100 m upstream of the WWTP (Flow monitoring, Figure 3) and summed up contributions of the successively emptied CSOTs. Due to this, each graph represents the addition of another discharge curve hydrodynamically modelled with InfoWorks CS®. A roughness coefficient of 5 mm provides a very good match compared to the monitored data. In table 1, the measured flow times for each catchment are compared to results from simple calculations. It can be concluded that the results are very close. Incorrect data can be identified according to outliers (Nocher-Route, Büderscheid and camping Bissen). Consequently, these errors (e.g. from old design data, differently built structures or incorrect data input) are considered by adjustments (e.g. length of pipes or slopes). Calibration of the nonlinear hydrologic model includes estimating the Manning coefficient for roughness ($n_{Manning}$) and the number of tanks in series for the description of the cascade ($n_{Cascade}$). Figures 5 and 6 illustrate the selection of appropriate values for $n_{Manning}$ and $n_{Cascade}$ for adequate model calibration according to the monitored data from the FTT. Calibration of the cascade is done for $n_{Manning} = 0.013$ corresponding to centrifugally spun concrete as used for sewers (figure 5). Next, the appropriate roughness is determined iteratively (figure 6). Figure 7 shows the results for $n_{Manning} = 0.015$ (Brickwork) and $n_{Cascade} = 7$. A comparison with the results from hydrodynamic modelling demonstrates the quality of the calibration. Real differences are only found for the 4th peak at 13h30 which is a composition of discharges from Eschdorf, Goesdorf and Camping Bissen. Since the monitored discharges during the test were only about half the magnitude usually encountered at the WWTP inlet a validation of the determined parameters is done for an antecedent rain event of ~40 mm. Figure 8 proves the good agreement between the modelled and the monitored flow rates. This demonstrates the transferability of the procedure to real rain data. The mismatch of the adjusting DWF after the event stems from incorrect discharge measurement data from the CSOT since the IFMD are not designed to measure such low flows.

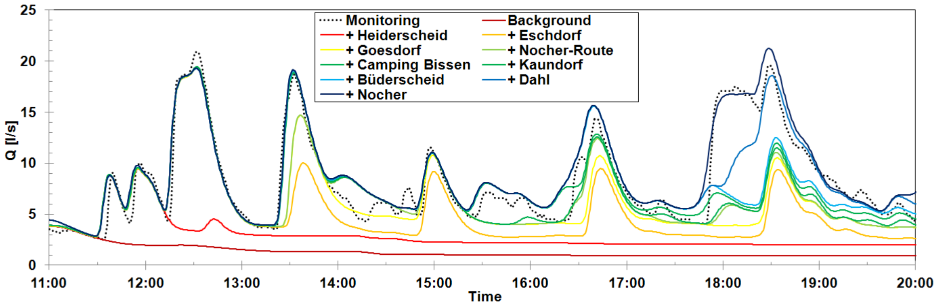

Figure 4 Allocation of discharge waves according to flow monitoring data

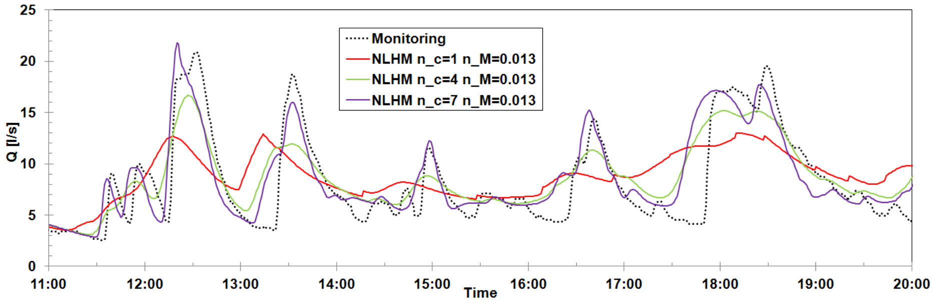

Figure 5 Hydraulic model calibration for CSF: number of tanks in series ($n_{Cascade}$)

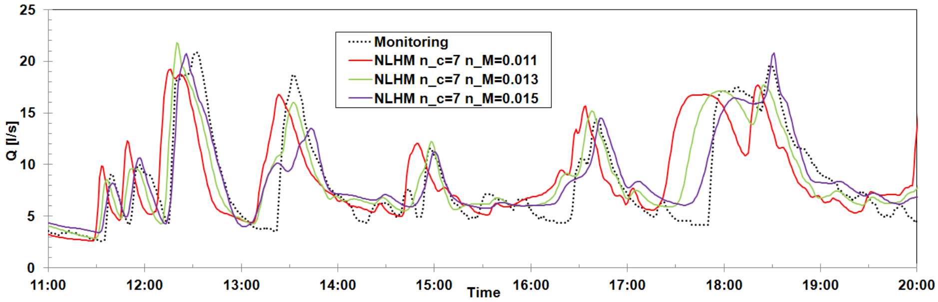

Figure 6 Hydraulic model calibration for CSF: Manning number ($n_{Manning}$)

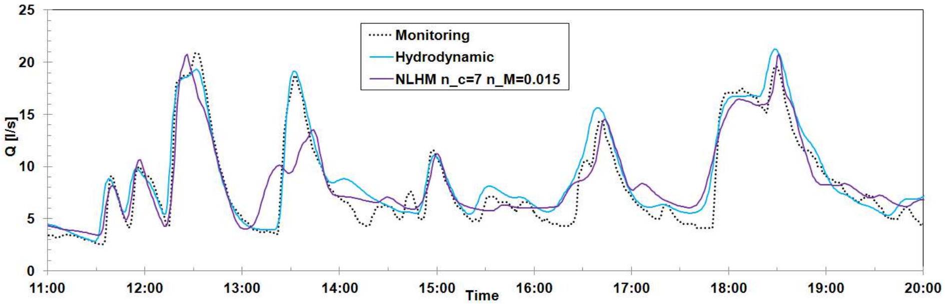

Figure 7 Hydraulic model calibration: comparison of different approaches

Table 1 flow times calculation: comparison

	Flow times [min]			**Error** [min]
Catchment	**Monitoring**	**Calculation**		
Heiderscheid	36	35	97.2 %	-1
Eschdorf	40	34	85.0 %	-6
Goesdorf	67	70	104.5 %	+3
Nocher-Route	150	117	78.0 %	**-33**
Kaundorf	143	147	102.8 %	+4
Büderscheid	78	89	114.1 %	**+11**
Camping Bissen	23	31	134.8 %	**+8**
Nocher	108	104	96.3 %	-4
Dahl	107	107	100.0 %	0
AVERAGE	83.6	81.6	101.4 %	-2

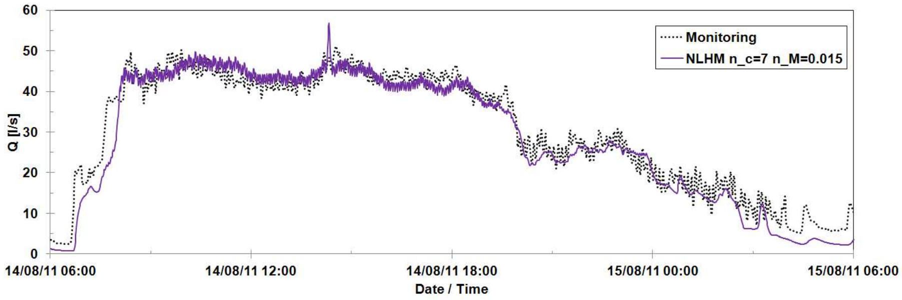

Figure 8 Hydraulic model calibration: Validation for a preceding rain event

From the flow monitoring during the FTT upstream of the WWTP a daily DWF per PE of 190 l can be derived. Based on the average daily DWF pattern gathered on catchment level the DWF hydrograph at the WWTP inlet was calibrated. Starting from the parameter set derived from the FTT calibration the number of tanks in series was reduced to the minimum while optimizing the Manning coefficient. Figure 9 demonstrates that the average DWF can be modelled with only 1 tank and $n_{Manning} = 0.030$ (corresponding to natural streams).

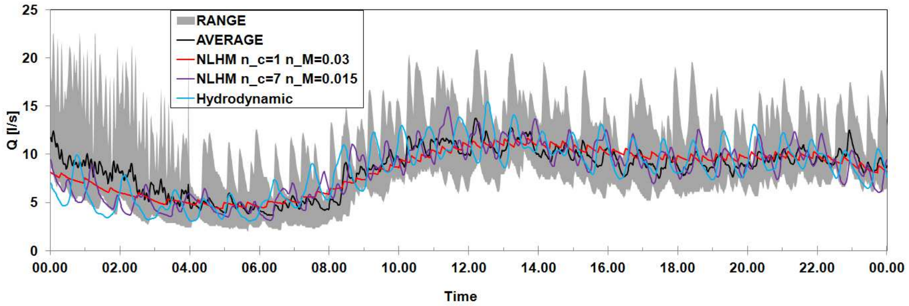

Figure 9 Hydraulic model calibration for DWF: Comparison of approaches

The FTT model parameterization causes a much more turbulent hydrograph than the parameter set for DWF. Fluctuations are caused by pump activities in the transport sewer network. From figure 9 it can be seen that all compared hydrographs are in the range of the usual DWF and the corresponding WWTP operation. From the point of view of integrated operation the resulting load is important. Therefore, conclusions depend on the results from pollution load modelling. However, in contrast to the results from the calibration for the FTT data, effects of variations of the number of tanks in series and $n_{Manning}$ are on a much smaller scale and according to daily averages negligible which is due to the small discharges and temporal variations during DWF.

5.2 Pollution load calibration

Figure 10 shows the input data for pollution load modelling using the example of the total Kjeldahl Nitrogen (TKN) according to effluent data (consisting of the normalised CSOT discharge and concentrations) from catchments with (i) free surface flow and (2) pressure flow to the WWTP. Concentration data show clear differences resulting from storage and accumulation in pass through tanks with pumping stations. Results for the calibration are presented in figure 11. According to the advective nature of the Lagrange model the results are dominated by the hydraulic calibration. Again, agreement is better for the DWF parameter set, but differences are not substantial. Both parameter sets show smaller concentration fluctuations compared to the hydrodynamic model because of dispersion effects. It can be concluded that also for pollution load modelling during DWF the Lagrange model is due to its advective nature quite insensitive to the hydraulic calibration. It delivers good results with the exception of the night hours which results from differences in data monitored at catchment level and at the WWTP.

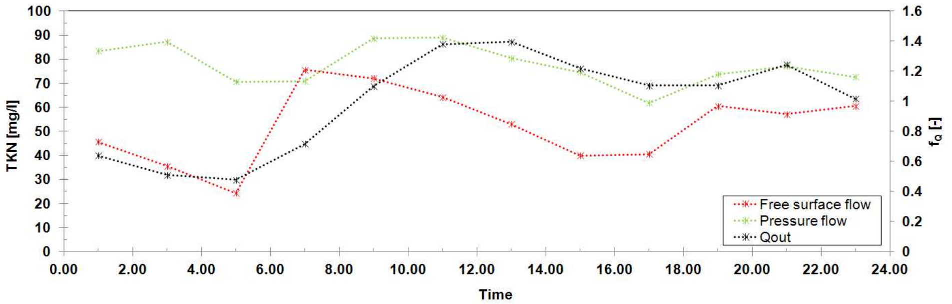

Figure 10 Measured average DWF effluent TKN concentrations at CSOTs

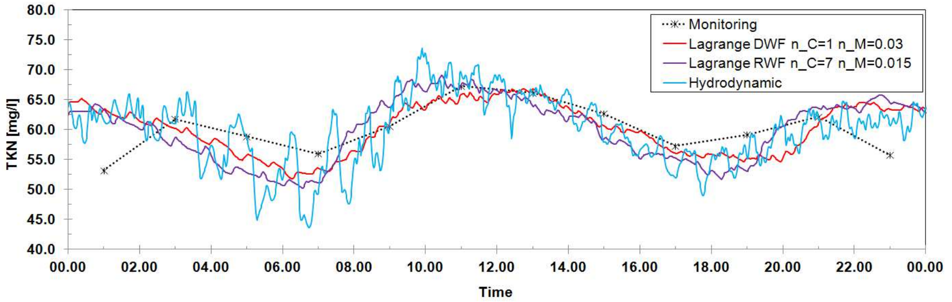

Figure 11 Pollution load model calibration for TKN: comparison of approaches

6 CONCLUSIONS AND RECOMMENDATIONS

The study shows that a simple test can provide important information about the implementation of design data in simulation software and therefore contributes significantly to model calibration. The generated combined sewage flow data allows for good calibration of a NLHM that closely resembles results of a hydrodynamic model calibration. The hydraulic model is limited to a transport sewer network where discharges are controlled according to the capacity of the WWTP where backwater effects are negligible. Consequently, non-linear hydrologic modelling is recommended for its smaller computational load. Even if the artificial wastewater discharges during the test reach only about half of the magnitude of real events the derived parameter set could be validated by data from a real event. For CSF the NLHM turns out to be quite sensitive to the model parameters while for DWF calibration is more difficult because the model is less sensitive. Therefore, it must be decided from the results of each case study which parameterization is appropriate and if case dependent parameterization would lead to better results in the framework of integrated modelling of wastewater systems. In the present case different parameter sets for DWF and CSF do not lead to significant improvements considering the resulting increase in computational effort.

ACKNOWLEDGMENTS

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