Evaluation of Characteristics of a Sewer System by Generation of Discrete Discharges from CSO Structures

Évaluation des caractéristiques d'un réseau d'assainissement unitaire par la génération de rejets discontinus de déversoirs d'orage

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RÉSUMÉ

Pour de multiples raisons, la connaissance détaillée du comportement hydraulique réel dans un réseau d'assainissement est d’une grande importance. Ceci inclut par exemple la validation des débits dans le système ou des paramètres d’un modèle hydraulique. L'étude présentée dans cet article porte sur la génération de rejets discontinus de déversoirs d’orage (CSO) et la détection des vagues correspondantes à l'entrée de la station d’épuration (STEP). L'objectif primaire de ce test de détection de débit discret (DDDT) était d'évaluer le temps d'écoulement dans les différentes canalisations entre les déversoirs d’orage et la station d’épuration. Les résultats ont été utilisés pour calibrer un modèle réduit intégré dans une approche de contrôle prédictif du réseau d’assainissement. L'analyse détaillée du test a révélé que les résultats contiennent beaucoup plus d'informations sur le système que prévu. Ils ont été, entre autres, utilisés pour la calibration fine du modèle hydraulique détaillé, pour la validation des mesures des débitmètres au niveau de la sortie des trop-pleins et pour détecter des infiltrations d'eau dans les diverses section du réseau d'assainissement. En raison de la simplicité de son application et de son évaluation, ce test DDDT a un potentiel d'application relativement vaste.

ABSTRACT

Detailed knowledge of the real hydraulic behaviour of a sewer network is of high importance for numerous purposes. This includes for instance the validation of volume flows in the system and of parameters for a detailed hydraulic modelling. The study presented here focusses on the generation of discrete discharges at individual combined sewer overflow (CSO) structures and the detection of corresponding flow waves at the inflow of a downstream waste water treatment plant. The original objective of the discrete discharge detection test (DDDT) was to evaluate flow times in different transport branches between CSO structures and a waste water treatment plant of a sewer system. The results were implemented in a simplified hydraulic model of the network used for a model predictive control application. The detailed evaluation of the test showed that the results provide much more valuable information on the system than expected. It was used to calibrate a detailed hydraulic model of the network, to validate flow monitoring devices in the outflow of individual CSO structures, and to account for infiltration to the transport sections under investigation. Due to its simple implementation and evaluation DDDT has the potential for a wide application.

KEYWORDS

Combined sewer systems, flow monitoring, generating discrete discharges, flow volume analysis, hydraulic characteristics

1 INTRODUCTION

Monitoring campaigns for a detailed observation of volume and substance flows in complex sewer systems require high personal and equipment expenses. Due to this, even extensive monitoring campaigns rarely focus on a detailed system wide observation of all structures in a sewer system at the same time. Apart from that, monitoring devices permanently installed in sewer systems are often not supposed to provide detailed monitoring data the possible range of discharges or concentrations. This is for example the case for flow monitoring devices in the outflow of combined sewer overflow (CSO) structures to downstream sewer sections exclusively used to control combined sewage flows on local level during rain events. Accordingly, insufficient flow rates observed in dry weather flow periods are simply not of interest for standard system operation. Consequently, the availability of reliable flow data is limited wet weather conditions, although installed flow monitoring devices continuously provide flow data. In this context a single flow measurement at the outflow of a sewer system under observation, respectively at the inflow of a downstream waste water treatment plant (WWTP) can provide valuable information on the upstream sewer section including structures like CSO tanks or pumping stations.

This is the background of the study presented here. In the framework of a project focussing on the implementation of a real time control system, a flow monitoring device was installed upstream of a WWTP. Main goal of the campaign was to assess the flow times in the transport sewer sections in between upstream CSO tanks (CSOT) or pumping stations and the downstream WWTP under conditions of combined sewage flow. To evaluate the flow time in specific sewer sections, a discrete discharge detection test (DDDT) was carried out to generate discrete discharges to the downstream WWTP. The detection of the discrete discharge waves at a location unaffected by the downstream the WWTP allowed an estimation of the flow times in the individual sections.

Further, the DDDT provided additional information on hydraulic characteristics of the transport system, infiltration inflow, DWF volume of upstream sub-catchments, the accuracy of flow and water level monitoring devices of upstream structures etc. The data was used to improve a model of the sewer system implemented in hydraulic simulation platform InfoWork® CS (Innovyze®), as well as to validate a simplified model of the system implemented in SIMBA® sewer (Regneri et al., 2012). Moreover, the hydraulic simulation of the system supported the detailed evaluation of the test.

2 METHODOLOGY

2.1 Implementation of the discrete discharge detection test

The DDDT was carried out during dry weather conditions in the Haute-Sûre sewer system in the north of Luxembourg. Figure 1 illustrates the sections of the new drainage network in operation in 2011. 8 CSOTs and a sanitary sewer of a camping site are connected to the transport system upstream the WWTP. The outflows of 3 CSOTs and of the camping site are pumped into the downstream interceptors. For the test a temporary flow measurement OCM PRO (NIVUS, Germany) was installed in the sewer upstream the WWTP (s. Figure 1). The device included an ultrasonic water level measurement probe installed at the pipe crown measuring downward. Further, it included an additional ultrasonic sensor for flow velocity detection in the flow cross section based on the cross-correlation method, installed eccentric close to the pipe invert (s. Figure 2). For low water levels (≤0.1m) the water levels monitored by the air ultrasound sensor mounted in the pipe crown were processed to get the flow rates. Accordingly, for low water levels the flow rates resulted from the product of the flow velocity calculated by Manning's formula for gravity flow and the cross-section area of flow. For higher water levels the flow velocity detected by the flooded lower sensor were taken into account for the flow rate calculation. Linked to that, it was assumed that the submerged flow velocity probe does not significantly disturb the cross-section area of flow. The monitoring location was upstream of the backflow level of the inflow pump sump of the WWTP to avoid an impact on gravity flow conditions.

The magnetic-inductive discharge (MID) measurement, monitoring the inflow pumped to the WWTP could not be used to gather detailed flow information, because of the time delay linked to the pumping intervals of the inflow pumps. However, the permanent inflow measurement of the WWTP was used to validate the overall volume balance, resulting from the temporal observation of the outflow of the system. Besides the inflow of the WWTP all outlets and pressure lines downstream the CSOTs are equipped with MID flow measurement devices. Further, all the CSOTs are equipped with permanent water level measurement devices based on hydraulic pressure monitoring. The data was collected and stored in a centralised data base at the WWTP and available for the evaluation of the test.

The applied test procedure of mimicking wet weather flow in individual sewer sections included several steps of controlled interventions deviating from standard operation mode of the system. The control of the concerned operating parameters was done by SCADA system from the control room in the WWTP. In a first step, the inflow to the transport network was stopped by closing the outflow valves, respectively switching off all pumps that are feeding the system. After a specific duration of storing dry weather flow in the storage structures, the valves were opened and pumps switched on step by step, following a predefined schedule. The time planning was closely linked to expected flow times in the network shown in table 1. The estimation of flow times was based on the expected flow taking into account structural information of the sewer system, and the partially filling function for circular pipes specified in Hager (2010).

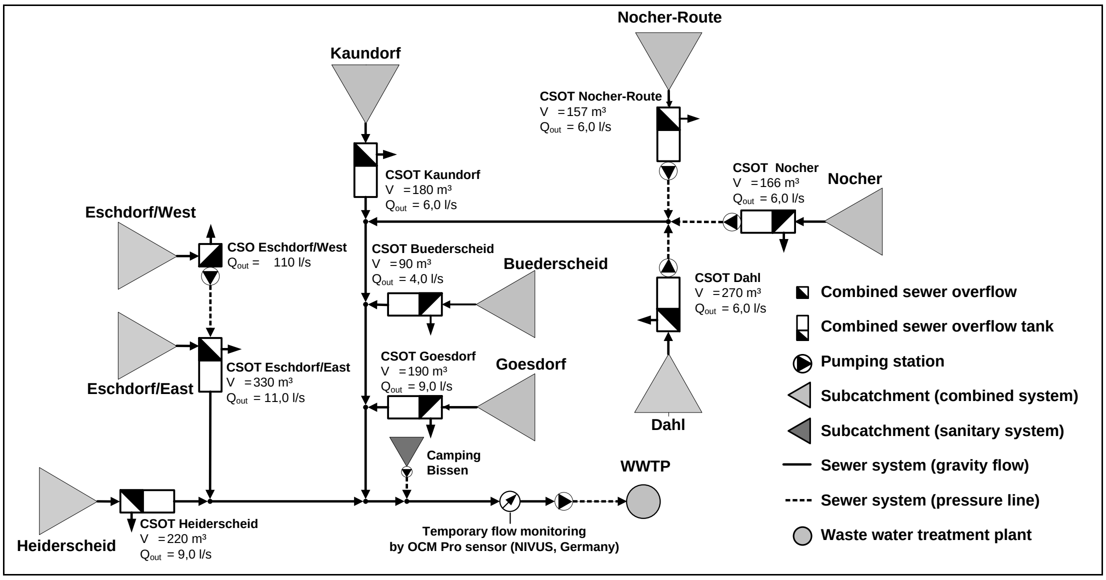

Figure 1: Schema of the Haute-Sûre sewer network

At the day of the DDDT the outflow of all local structures to the transport sewer was stopped at 9:00. Figure 3 illustrates the schedule and the monitored flow rates of the discrete discharges generated at individual structures after a minimum storage time of 2h in the structures. The objective of the schedule was to create a discrete discharge waves at individual structures which are clearly attributable to single structures or to a maximum of two structures (e.g. CSOTs Nocher and Dahl) at the location of the temporal flow monitoring upstream the WWTP. Especially, the pump at Camping Bissen had to be switched on several times during the test to avoid an exceedance of the pump sump capacity. Due to technical problems the schedule had to be adapted during the test. For instance, the valve of CSOT Goesdorf could not be opened by remote control and had to be opened manually on site.

Figure 2: Temporary flow monitoring location OCM Pro (NIVUS) upstream WWTP

Further valuable information is shown in figure 3. The outflow hydrograph of CSOT Eschdorf/East shows temporally high flows caused by the upstream pumping station at CSO Eschdorf/West. Moreover, the flow monitored in the effluents of CSOTs Heiderscheid, Kaundorf, Buederscheid and Goesdorf are temporarily or permanently fluctuating close to zero after the emptying of the tanks. This indicates a low accuracy of local inductive flow monitoring devices during DWF conditions since the valves were kept open after the tanks were emptied.

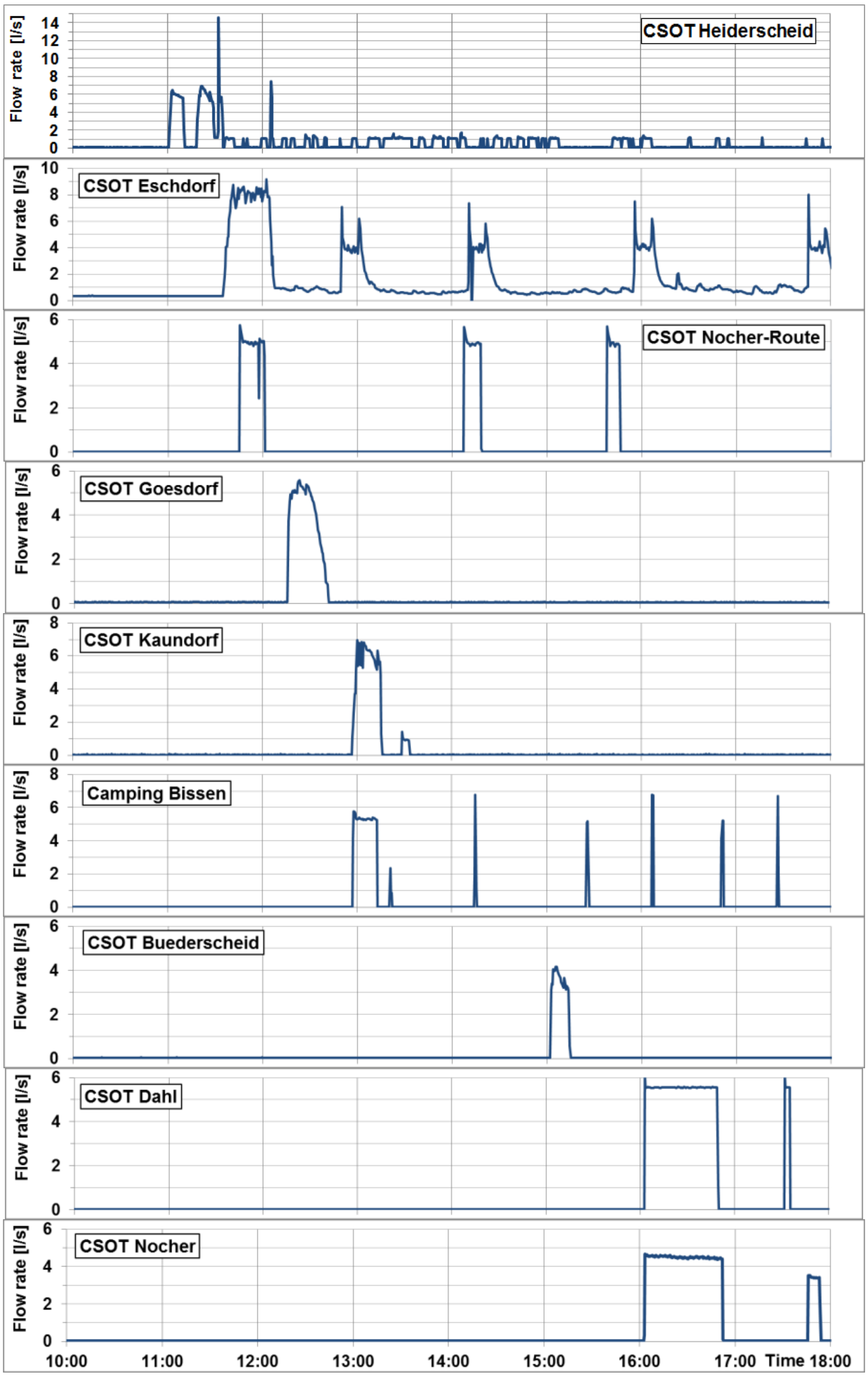

Figure 3: Schedule and outflow rates of structures during DDDT

2.2 Evaluation of DDDT using monitoring results and hydraulic modelling

At first, the data measured by the temporal flow monitoring device upstream the WWTP was verified by balancing the flow volume during the test from 9:00 to 18:00 taking into account the inductive inflow measurement downstream the inflow pumps of the WWTP.

For the evaluation of the DDDT data observed by stationary monitoring devices in the individual structures was considered in addition to the data of the temporal flow monitoring. In connection with geometric characteristics of the structures, the water level enabled an assessment of the sewage volume stored in the structures during the test. Additionally, the flow rate monitored by the temporally installed device observed at the beginning of the test indicates the background flow in the system without the contribution of the sub-catchments.

Subsequently, the flow rates observed at the outlet of all individual structures were used as input data to an InfoWorks® CS model of the observed transport sewer sections. The comparison between the simulated hydrograph at the location of the temporary flow measurement and the observed flow curve, provided information on the accuracy of the input parameters to model the system:

1. Flow measurement in outflow of individual structures
2. Average roughness coefficient in sewer system
3. Slope in the sewer sections under investigation
4. Accuracy of information on structures in sewer system (e.g. gradients in the systems etc.)

The average gradients along the sewer sections under investigation reflect the characteristics of the related terrain. Hence it was assumed that the impact of inaccurate pipe gradients in the input parameters is negligible.

Taking into account the volumetric load to the WWTP of about 604m³ on the day of the test and the characteristic distribution of volume flows during an average dry weather day, the individual daily inflow curves (2h-average) to the tank structures were estimated. The distribution of dry weather flow volume to the single sub-catchments upstream the CSOTs was done proportionally to the connected population equivalents (PE). The resulting dry weather inflow curves were validated by comparing the calculated dry weather inflow volumes to the CSOTs in the filling period with activated storage volumes at the end of the period.

The estimated dry weather flow curves for the single catchments were included as input data for the next runs of the hydraulic model of the system. The data was used to replace the outflow rates of the tanks after the emptying of the storage volume. In the final runs of the hydraulic simulation the hydraulic roughness coefficient of the pipe material used for the modelling, was adjusted to fit the simulated hydrograph to the one observed.

The main aim of the DDDT was to estimate the flow times in the sewer system. Concerning this, the estimated flow times based on Hager (2010) were compared to the flow times resulting from

1. Flow peaks observed by the temporal flow monitoring upstream the WWTP attributed to individual discharge waves from CSO structures
2. Hydraulic simulation of the transport sewer system.

3 RESULTS AND DISCUSSION

3.1 Evaluation of volume flows in the system

The accumulated outflow volume of the system during the test detected by the temporary monitoring, and by the inflow monitoring of the WWTP is shown in Figure 4. The flow volume detected during the test by the temporary flow monitoring of 193m³ is in line with the volume detected by the WWTP inflow measurement. As expected, the volume pumped to the WWTP is above the volume detected by the upstream flow monitoring from 11:00 to 12:00. This is because some flow which passed the upstream flow monitoring before 11:00 is pumped into the WWTP. From about 12:00 on, the accumulated inflow volume to the WWTP follows the accumulated volume monitored upstream. This changes at about 17:15 when the WWTP inflow volume exceeds the volume monitored upstream. This indicates a slight underestimation of the flow volume observed upstream the WWTP inflow.

Furthermore, figure 4 illustrates the accumulated outflow volumes monitored in the effluent of all upstream structures feeding the transport system. The accumulated flow volume detected at the outflows of the upstream structures of ca. 129m³ is clearly below the volume flow detected at the outflow of the system. This is not only due to the flow times in the sewer system, but indicates an infiltration inflow to the transport sewer sections and/or inaccuracies of all or some outflow measurements at upstream structures. The observed outflow rates detected at the CSO structures are used as input data for the first run of hydraulic simulation of the transport system. Consequently, the accumulated flow volume at the system outflow resulting from the first simulation run is also significantly below the observed outflow volume of the system (s. figure 4). Thus, the individual outflow rates of the upstream structures were estimated based on the assumptions specified in chapter 2.2.

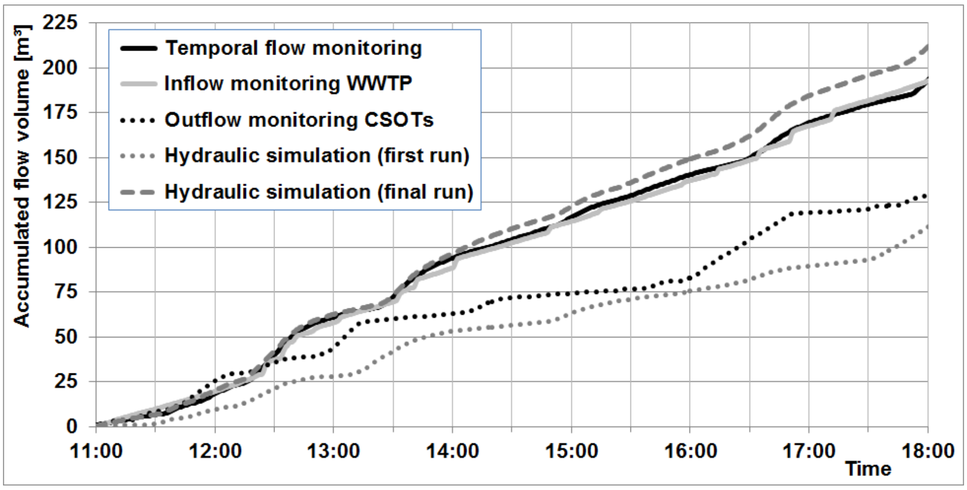

Figure 4: Accumulative flow volumes resulting from temporal flow monitoring, WWTP inflow measurement, monitored CSOT outflows, and hydraulic simulation runs

3.2 Hydraulic modelling of the system

Figure 5 illustrates the flow rate detected by the temporary flow monitoring upstream the WWTP during the DDDT. A lot of the detected flow peaks are clearly attributable to discrete outflows of upstream structures like for Heiderscheid, Eschdorf, Bissen and Kaundorf. Other flow peaks reflect an interaction of outflow peaks at the location of interest.

2,5h after the closing of the CSOTs outflow valves the downstream transport sewer sections are expected to be empty. Therefore the minimum flow rate of about 2.5l/s observed at about 11:30 right before the first flow wave from Heiderscheid reaches the monitoring location is an indication of the background flow in the system caused by infiltration. It also may include a small amount of delayed flow from upstream CSOTs. For a more accurate quantification of the infiltration the interruption period of upstream inflows to the transport system at the beginning of the test should be extended.

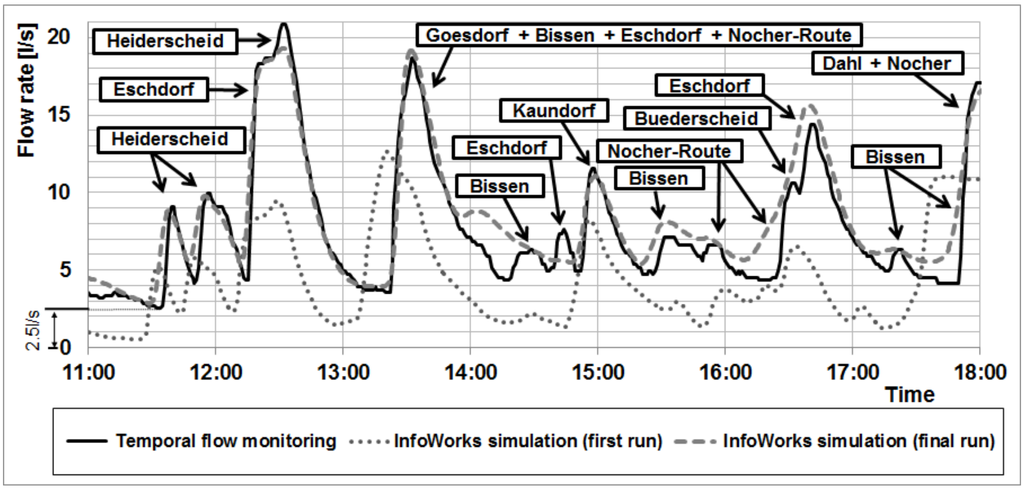

Figure 5: Observed flow rate and simulated flow curves upstream the WWTP inflow

The simulated flow rate for the first run of the hydraulic modelling of the system shown in figure 5, illustrates the significant underestimation of the flow peaks. Linked to that, a continuous background flow of 2.5l/s was implemented as input parameter in subsequent simulation runs. Additionally, for the periods before the closing of the outflow valves and after the emptying of the tanks, the calculated dry weather flow curves were used as flow input to the hydraulic model. This is based on the assumption that the monitoring devices at the outflow of tanks emptied by gravity flow do not provide correct flow data during DWF conditions. The Reason for this may be very low flow velocities or a free surface flow at monitoring locations in dry weather conditions both hampering inductive flow measurement.

Figure 6 shows the difference between the monitored outflows and the updated dry weather flow after the emptying of the storage volumes taking the example of CSOT Heiderscheid. The periods of fluctuating very low flows after emptying the tank, suggest that the flow measurement does not provide reliable data in some periods of time. Contrary to that, the updated flow obviously causes an overestimation of the tank effluent during DWF periods.

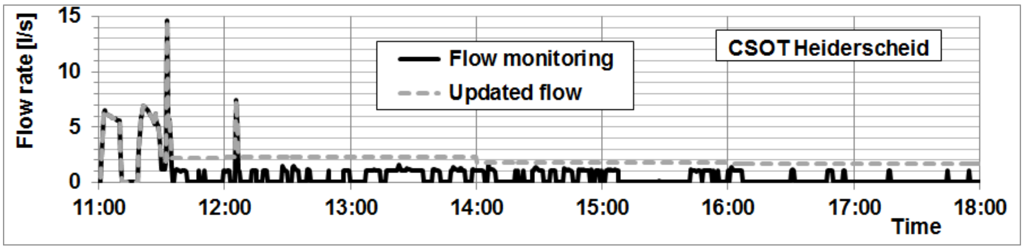

Figure 6: Observed flow rate and simulated flow curves upstream the WWTP inflow

Moreover, in the first simulation run especially the modelled flow waves from more distant structures obviously reach the location of interest faster than in reality (see figure 5). Due to the fact that length and slope of the sewer sections is known in detail, this could be caused by inadequate roughness coefficients used for hydraulic modelling. For the first simulation run a roughness coefficient of 0,0015mm recommended for pipe materials like smooth concrete was included in the structural model parameters. In the final modelling run a roughness coefficient of 0.005mm representing the roughness of smooth bricks was taken into account.

The simulated flow curve for the final simulation run illustrated in figure 5 shows the significant improvements of the hydraulic model compared to the first run. However, differences for some peak flows as well as a permanent overestimation of the flow rate by the model after 15:00 confirm expected deviations of the adapted DWF curve from real DWFs in the individual sub-catchments. This can be caused by calculating with an inadequate number of PE or by a significant variation of water consumption per PE in the single sub-catchments. Moreover, this may also be caused by different infiltration inflows to the sewer systems in the catchments upstream the CSO structures.

3.3 Assessment of flow times in the system

Figure 7 illustrates the procedure of the estimation of flow times in the individual sections of the transport system based on observed flow data taking the example of Heiderscheid and Eschdorf. For both transport sections the procedure allows for a clear estimation of the flow times linked to the duration from the opening of the outflow valve until the detection of the flow wave at the temporal monitoring location. The procedure results in a flow time of 36min for CSOT Heiderscheid and 40min for CSOT Eschdorf. For flow waves from other structures the flow times could not be detected so clearly. This was for instance the case for the discrete discharges from CSOTs Nocher-Route, Goesdorf and Buederscheid to the WWTP.

The model based evaluation of the flow times included several runs of the final hydraulic model. In a first run only the outflow contribution of CSOT Heiderscheid is modelled as input to the transport system (s. figure 8). In the next runs the contributions of the other tank outflows are added incrementally in chronological order related to the opening times of the valves. The illustrations of the simulated flow curves caused by the single tank outflows at the monitoring location upstream the WWTP in figure 8 explains the procedure for CSOT Heiderscheid and CSOT Eschdorf.

The results of the three approaches to estimate the flow times in the transport system are shown in table 1. For most of the tanks the results differ within a range of 3min to 8min. Almost all flow times resulting from the simulation based evaluation, exceed the flow times resulting from the other approaches. The discrepancies in the findings based on the three approaches are higher for Kaundorf (9min), Buederscheid (16min) and Nocher-Route (33min). This implies that the characteristics of the sewer system in some specific sections are still not taken into account adequately in the model. There was no following investigation since the found flow times were within the range of accuracy needed for the development of a model predictive control of the network Schutz et al. (2012).

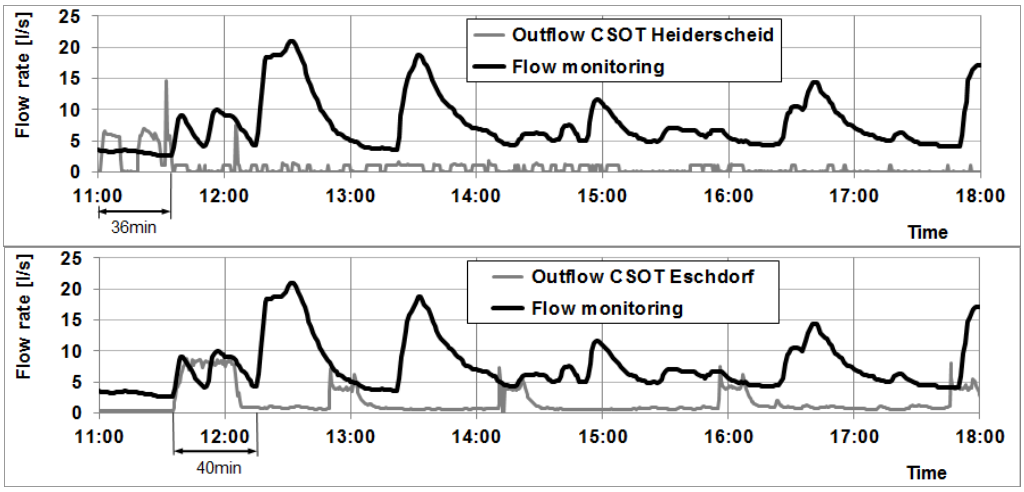

Figure 7: Flow time estimation using observed flow curves taking examples of CSOTs Heiderscheid and Eschdorf

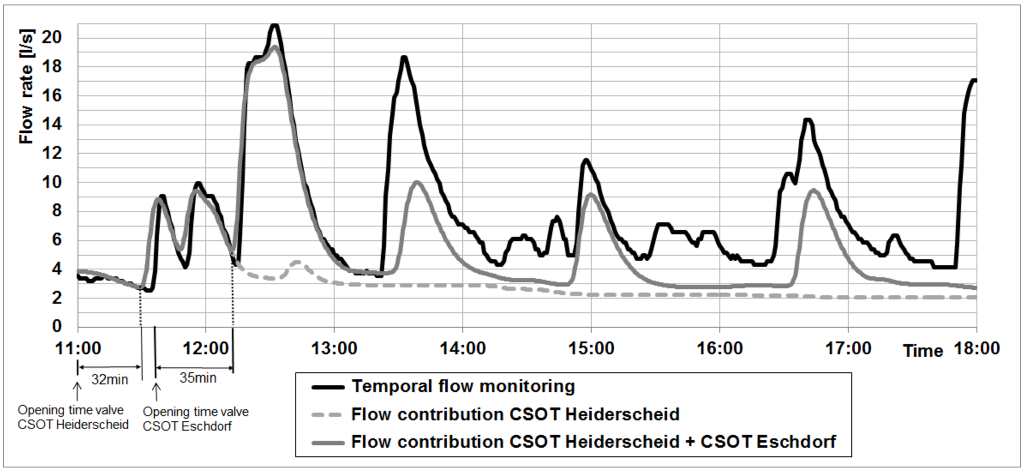

Figure 8: Flow time estimation using hydraulic modelling taking examples of CSOTs Heiderscheid and Eschdorf

Table 1: Estimated flow times in the transport sections of the transport network under investigation

	Estimated flow times [min]		
CSO Structure / pumping station	Based on Hager (2010)	Based on observed flow curve	Based on InfoWorks® CS modelling results
Heiderscheid	35	36	32
Eschdorf	34	40	35
Goesdorf	70	67	69
Nocher-Route	117	150	123
Kaundorf	147	143	138
Büderscheid	89	78	73
Camping Bissen	31	23	23
Dahl	104	108	110
Nocher	107	107	101

3.4 Volume balance for individual structures

In addition to the DDDT further evaluations of volume balances can be done using the data monitored at local CSOTs during the test. Here the local volume balances are based on the estimated Inflow to individual structures, the water levels measured in the tanks and the flow rate observed in the tank outflows to WWTP during the test. Three independent balances which should result in the same volume can be calculated and compared to assess possible sources of inconsistencies.

1. Maximum volume stored in tank ($V_{storage,max}$):
   Local water levels observed at the end of the filling period and the relationship between the water level and the geometry of the storage tank indicate the stored sewage volume
2. Inflow volume to the tank structures during filling period ($V_{in,filling}$):
   Accumulated volume of estimated dry weather inflow to the tank the in filling period
3. Outflow volume during the emptying of the tank caused by $V_{storage,max}$ (V_{out}):
   Accumulated volume of monitored tank outflow minus the estimated tank inflow in the emptying period

Table 2 shows the results of the volume balances for the CSOTs Goesdorf and Dahl. For CSOT Goesdorf the difference between the inflow volume of 16.2m³ in the filling period and maximum volume stored in the tank at the end of the filling of 14.7m³ is only 1.5m³ (ca. 10%). The findings confirm that the inflow to the structure might be slightly overestimated by the applied approach of assigning DWF curves to the sub-catchments.

Moreover, the tank outflow volume dedicated to the maximum volume stored in the tank at the end of the filling period is only 3.6m³. This is significantly below dedicated stored volume and inflow volume to the tank. This might indicate that the inductive flow monitoring device installed in the outflow of the structure might not provide correct flow rates. Due to a malfunction of the remote control of the valve, already mentioned in chapter 2.1, the opening time of the outflow valve was not in line with the originally planned schedule. Consequently, the discrete discharge from Goesdorf was overlapped by discharges from Eschdorf, Bissen etc. (see figure 5). Due to that, a reliable validation of the outflow volume from Goesdorf by the temporary flow rate measurement installed downstream was not possible. Overlapping flow waves can be avoided if the total duration of the DDDT is extended to wait for an emptying of the transport sewer sections after individual flow waves.

For CSOT Dahl the inflow volume in the filling period of 16.6m³ is above the dedicated outflow volume of the tank of 14.1m³ in the emptying period. In Dahl, the maximum volume stored in the tank at the end of the filling period of 28m³ is far above the results of the related volume balances. Potential reasons may be

- Inadequate installation of the pressure sensor monitoring the water level
  in the tank after maintenance ⇒ incorrect adjustment of the zero point of the measurement.
- Incorrect information about the geometry structures (differences planned and built structure)

Table 2: Inflow volumes, maximum stored volumes
and outflow volumes of CSOTs Goesdorf and Dahl

CSO structure	$V_{in,filling}$ [m³]	$V_{storage,max}$ [m³]	V_{out} [m³]
Goesdorf	16.2	14.7	3.6
Dahl	16.6	28.0	14.1

4 CONCLUSIONS

Main goal of the DDDT presented here was to estimate the flow times in the transport sewer system, connecting CSO structures to the downstream WWTP. Moreover, the test should provide information on characteristics of the system important for hydraulic modelling of the network. Accordingly, the overall planning of the test was geared to the objectives. Both of the original goals were reached since the DDDT gave

- Sufficient information on the flow times in the system
- Enabled an adjustment of the hydraulic roughness of the sewers for hydraulic modelling

Further, the test provided sufficient data to verify the correct implementation of the system in InfoWork®.

During the evaluation of the test it became clear that the data gathered by the temporally installed flow measurement and the permanent monitoring devices in the system, can provide much more information. This additional information includes the

- Validation of DWF volume contributions of the single sub-catchments upstream the CSOTs
- Verification of the permanent monitoring devices by calculating volume balances

Of course, the efficiency of the test in view of providing more information would have been much higher if the additional goals were already taken into account in the design of the test.

In addition, the implementation of the test showed that it is quite essential to act flexibly in case of unexpected incidents like malfunctions of monitoring or control devices. In this context some unfortunate decisions have been taken during the test presented here. For instance, it obviously was a mistake not to change the schedule of the test in reaction to the difficulties with the remote control of the outflow valve of CSOT Goesdorf.

A DDDT could provide much more information on the sewer system and on upstream the sub-catchments. Assuming an appropriate schedule including extended time periods before and in between opening of CSOT outflow valves the test could step by step provide additional or more detailed information on the

- Infiltration to the transport system
- DWF quality of the individual sub-catchments if sampling or online quality measurement at inflow to WWTP is included

Finally, DDDT seems to be a promising tool to get detailed information on the characteristics of a drainage network with only little effort.

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