Modelling Rainfall Dependent Infiltration and Inflow (RDII) in a separate sewer system in Huddinge, Stockholm

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Keywords
Coupled hydrologic-hydraulic model, RDII, MOUSE-SHE, rehabilitation measures.

Abstract
A catchment in Stockholm, Sweden, with a separate sewer system has historically experienced repeated flooding of buildings with basements. Earlier flow measurements show an extreme amount of Rainfall Dependent Infiltration and Inflow (RDII) in the sewer system. DHI has carried out additional flow measurements in the sewer system comprising automatic flow gauges over longer time and manual flow measurements during night time for momentary flow. A coupled hydrologic-hydraulic model has been set up over the area using the collected information, where MIKE URBAN describes the pipe system and MIKE SHE describes the geohydrology. The MOUSE-SHE model was calibrated using the flow measurements, and subsequently used to describe the present conditions. Thereafter, different measures were simulated and evaluated in terms of their potential for reducing RDII. The proposed measures comprised sealing of pipes and manholes in prioritized subareas together with measures for improving the stormwater runoff from certain streets. Simulation results of the sealing of pipes and manholes showed a 40% reduction of RDII volume, and improved stormwater runoff from streets reduced the RDII volume an additional 5-10%.

INTRODUCTION

Rainfall-Dependent Infiltration and Inflow (RDII) has since long time been recognized as an important source of operating problems in sanitary sewer systems. RDII is considered as the main cause of sanitary sewer overflows (SSOs) to basements, streets, or nearby streams and can also cause serious operating problems at wastewater treatment facilities (EPA, 2008).

RDII is generated when stormwater and groundwater entry faults in the sanitary sewer system. *Infiltration* is the water entering a sewer system and service connections from the ground through defective pipes, pipe joints or manhole walls. Infiltration is mostly related to a high groundwater table that is observed during a wet season or in response to a large rainfall event. *Inflow* is the water discharged into a sewer system and service connections from different sources, *e.g.*, downspouts, yard and area drains, foundation drains, manhole covers or cross connections from storm sewers and combined sewers.

The reduction of RDII using different remediation measures is a focal point of sewer system maintenance and rehabilitation. Local conditions can vary significantly between different sewer catchments, and hence the most cost-efficient measures will also vary. To accurately determine the RDII flow components and their contribution to the total sewer inflow is of great importance as well as to describe the effects of proposed remediation measures. Field measurements and computer modelling of sewer collection systems play an important role in determining sound and economical remedial solutions that reduce RDII, improve system integrity, reliability and performance, and avoid overflows. Rehabilitation planning in areas with RDII problems often demand a mixture of drainage measures and sealing measures, where the local conditions regarding geohydrology and land use first should be analysed.

In 2008-2009 DHI Sweden carried out a project for the client Stockholm Vatten regarding an area with a separate sewer system that historically has experienced repeated flooding of buildings with basements. Earlier flow measurements show an extreme amount of RDII in the sewer system. The main purpose of the project has been to present a guiding plan that facilitates the planning of measures required for reducing the RDII volume in the sewer system.

The concrete objectives with this project have been:

- to describe and analyse the geohydrological conditions within the catchment and the capacity of the sanitary sewer system
- to assess the sources of RDII
- to suggest suitable measures to reduce RDII and describe the effects of such measures with respect to levels and discharges in the sewer system

This paper presents the above-mentioned project with focus on the RDII modelling part.

METHODOLOGY

The area in question has a history of problems related to RDII, *e.g.* repeated flooding of buildings with basements. A coupled hydrologic-hydraulic model – MOUSE-SHE – was set up over the area and calibrated using flow measurements, and subsequently used to describe the present conditions. The model was thereafter used for simulating and evaluating different measures in terms of their potential for reducing RDII.

STUDY SITE

The area is located in Huddinge about 10 km southwest of the Stockholm city centre (Figure 1 left). The catchment is for the most part limited by the water divide interpreted from topographical data, see Figure 1 right. The size of the catchment is about 650 hectares and there are about 63 km of main sanitary sewer pipes with dimensions ranging from 0.1-0.8 meter. In the northeast the catchment is limited by Lake Långsjön and in the south by Lake Trehörningen. In general, the dominating runoff direction is from northwest to southeast. The northern part of the catchment is very hilly with a dramatic topography. In the southern part there are some sub-areas with large variations in elevation, but generally the topography is more flat here.

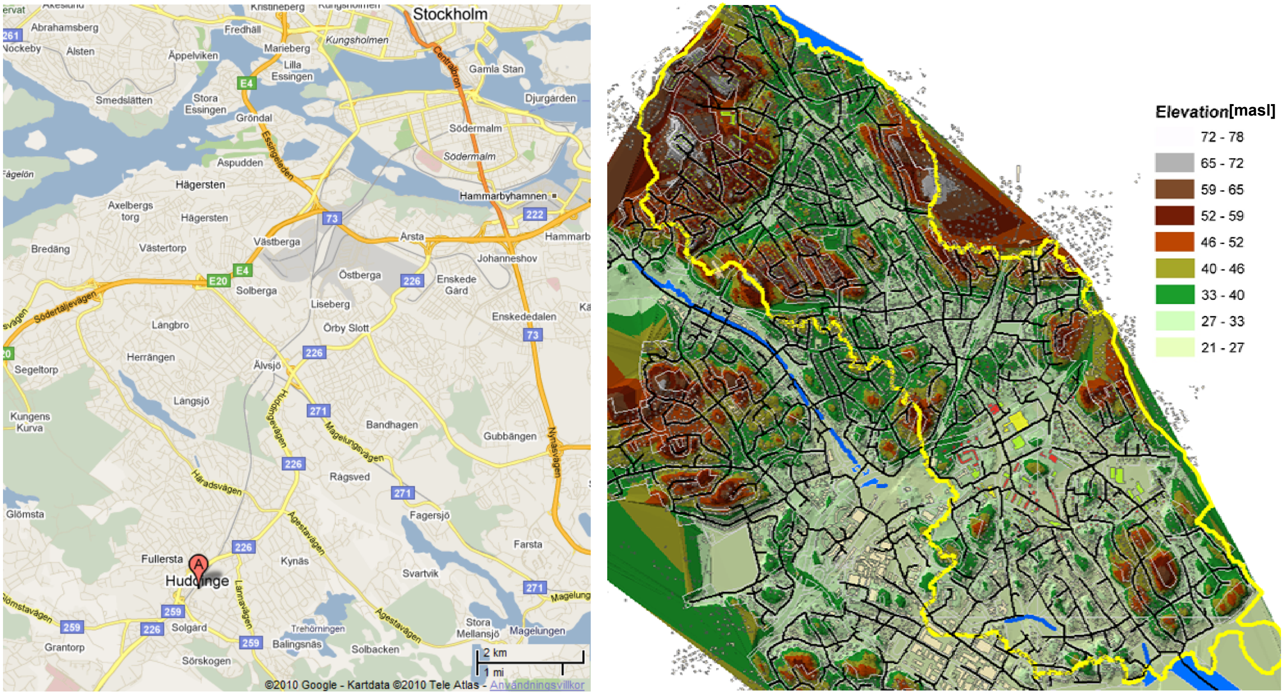

Figure 1: Overview (left); catchment, topography, sanitary sewers, streets and buildings for the model area in Huddinge (right).

Based on soil investigations and a soil map over the area, a geohydrological interpretation was performed. In the high elevation parts there are visible bedrock or thin layers with moraine on shallow bedrock. This is especially the case for the northern part, but is also seen in several smaller areas in the south. In the valleys and the low-lying areas, where the major part of the sewer system is located, the soil layers are mostly clay with moraine underneath. There are few water courses in the area, which means that the catchment is mainly drained by surface runoff to the stormwater system, by foundation drains or by direct infiltration to the sanitary sewer system. In the northern part of the area there are no roadside ditches or gully pots, which together with the fast runoff from surrounding areas with thin or no soil cover create complicated runoff conditions with high risk of local flooding during severe rainfall events. This in turn, implies an increased surface runoff to the pipe ditch with an increased risk for RDII inflow in areas where the sewer system is in bad condition.

FIELD MEASUREMENTS

Earlier flow measurements show an extreme amount of RDII in the sanitary sewer system. Within this specific project DHI carried out additional flow measurements in the sewer system comprising five automatic flow gauges and one start-stop level logging of a pumping station over longer time (September 2008- June 2009). Two rain gauges were also installed in the area.

The flow meter results from 2008-2009 follow that from earlier measurements, meaning that there is a strong influence by RDII in the hydrograph showing a slow runoff component with response time over several days, see Figure 2. For each rain event there is a following increase of base flow.

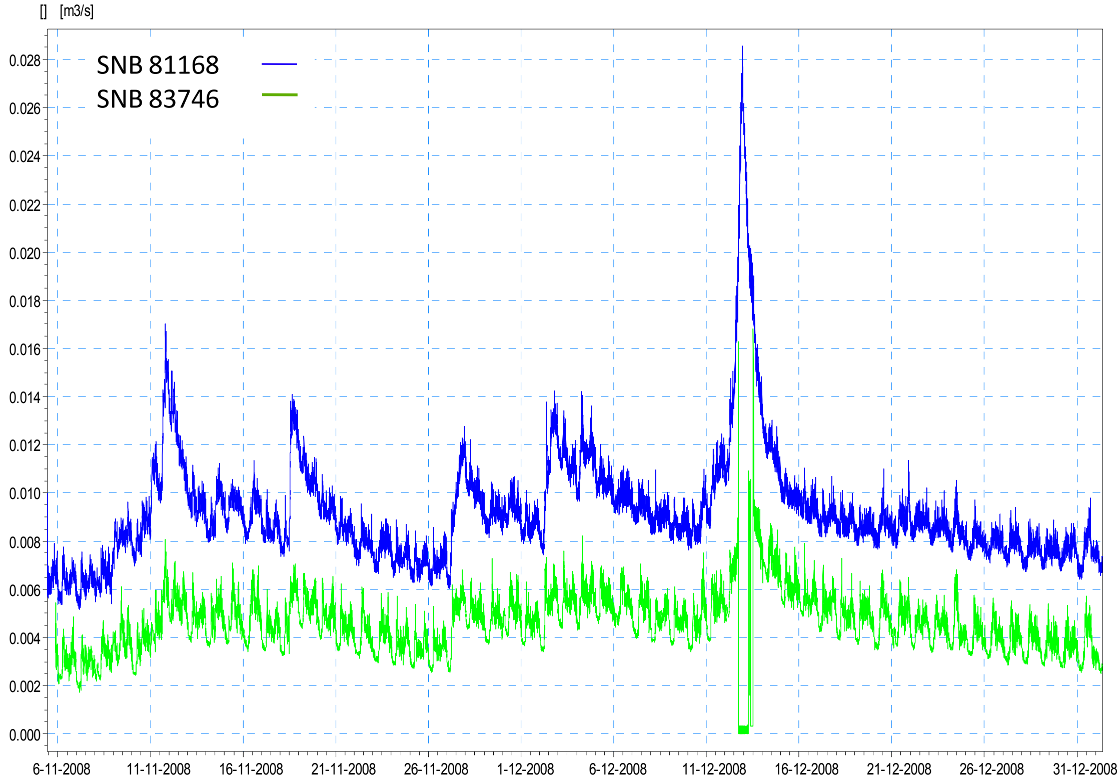

Figure 2: Example of gauged flow data, measured in the northern part of the catchment.

Manual flow measurements during night time for momentary flow were carried out within the project. First a comprehensive campaign in April 2008 which was preceded by a wet winter season. The results from this campaign, see Figure 3, show that it is the northern and southern part that have the largest amount of RDII compared with the middle part of the catchment. In total about 50 l/s of RDII was measured, of this 15 l/s and 30 l/s from the northern and southern part, respectively.

The above-mentioned results formed the decision to focus on the northern and southern part, and in December 2008 detailed manual flow measurements were performed in these areas, see Figure 4 and 5. The total momentary flows in the northern part and southern part were 27 l/s and 35 l/s, respectively.

In the northern part 73% of total RDII flow was found to be located along a total pipe length of about 4,000 meter, shown as red, orange and yellow areas in Figure 4, where the pipes in the red and dark-red areas collect the largest amount of RDII.

In the southern part 86% of total RDII flow was found to be located along a total pipe length of about 3,700 meter, shown as red, orange and yellow areas in Figure 5, where the pipes in the red and dark-red areas collect the largest amount of RDII.

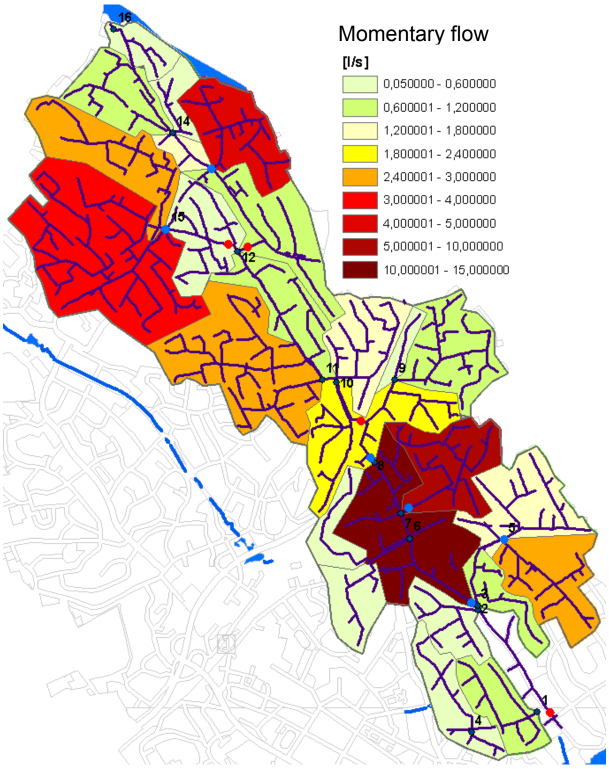

Figure 3: Sub-areas where momentary flows [l/s] were measured in April 2008.

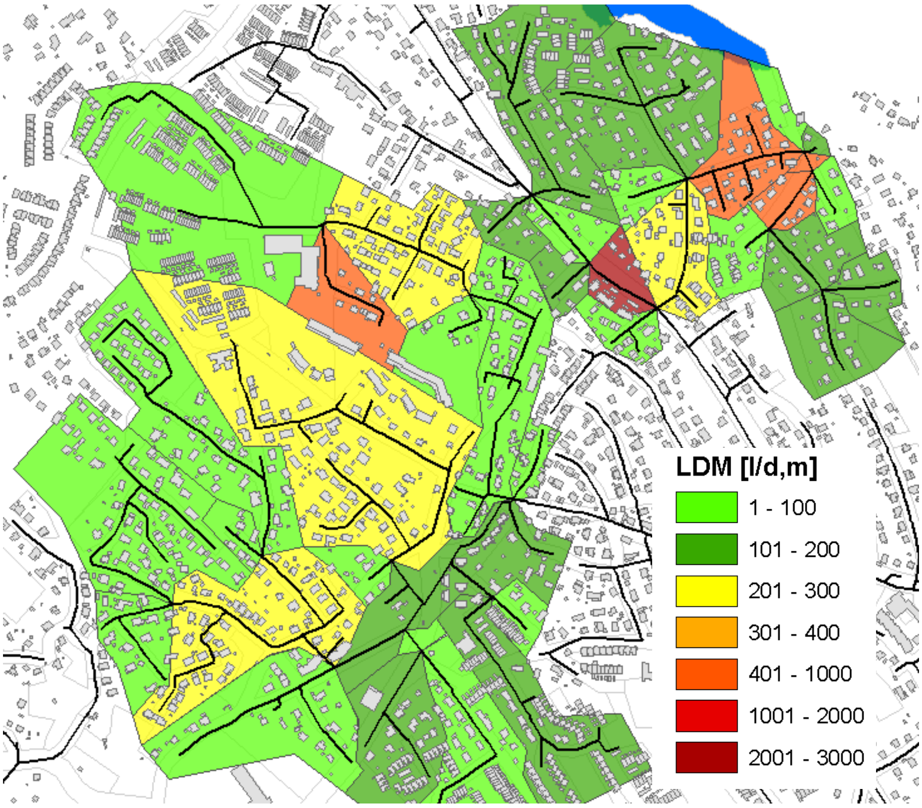

Figure 4: Sub-areas in the northern part where momentary flows were measured on the 10th of December 2008. Yellow, orange and red sub-areas have the largest amount of RDII, calculated as litres per day per meter pipe (LDM).

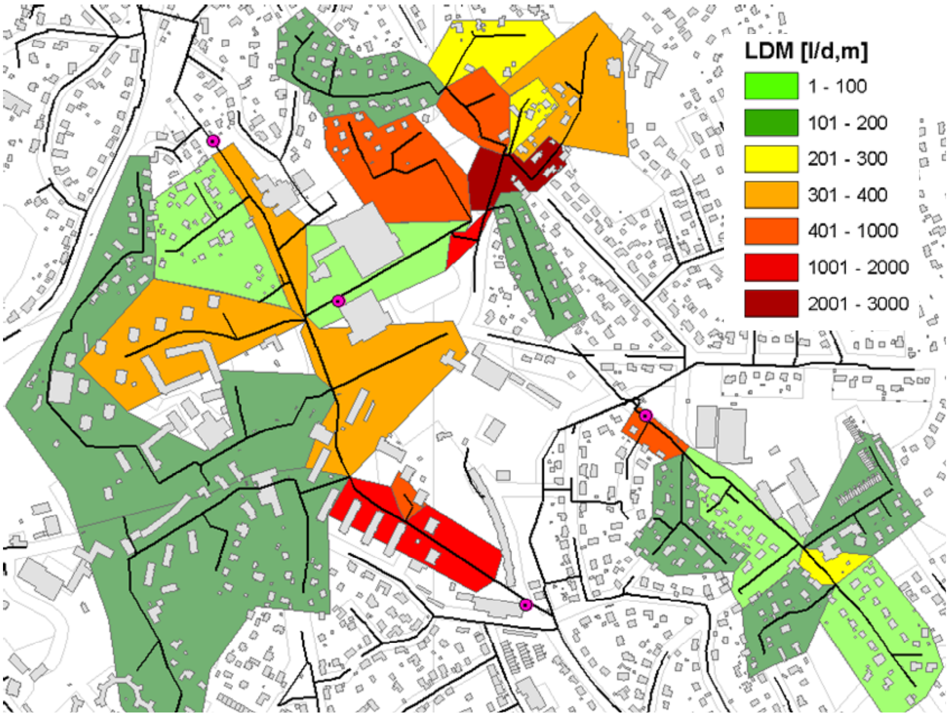

Figure 5: Sub-areas in the northern part where momentary flows were measured on the 17th of December 2008. Yellow, orange and red sub-areas have the largest amount of RDII, calculated as litres per day per meter pipe (LDM).

Additional field measurements included observations of groundwater levels and the pipes with the largest RDII inflows in the orange and red sub-areas in Figure 4 and 5 have also been subjected to TV-inspections. A survey of buildings with basements in the prioritised areas were also performed.

MODELLING

A model system called MOUSE-SHE was used to set up a coupled hydrologic-hydraulic model over the area, where MIKE SHE (MIKE by DHI, 2010a) describes the geohydrology and MIKE URBAN CS (MIKE by DHI, 2010b) describes the pipe flow in the sewer system. The dynamic coupling of the two models makes it possible to describe the groundwater-sewer interactions which are of importance in these kinds of RDII projects.

The input data to the MIKE SHE model include data on topography, land use, geology, hydrogeology and meteorology. The sanitary sewer system has earlier been described in MIKE URBAN and this model was provided by Stockholm Vatten and integrated with the geohydrological description in MIKE SHE. The MIKE URBAN model has earlier been calibrated with respect to dry weather flows and connected impervious areas.

Each pipe link was given a leakage coefficient which describes the rate of infiltration (or exfiltration). The leakage coefficient together with the pressure gradient between the groundwater surface and water level in the pipe give the leakage flow. Leakage coefficients were later calibrated with data from the momentary flow measurements.

Based on the input data above MOUSE-SHE calculates the water movement from rainfall to groundwater, water courses and pipe network. This means that the system calculates actual evapotranspiration, surface runoff, infiltration and water saturation in the root zone, groundwater levels and groundwater flows in different layers, groundwater outflow to water courses, drainage and leakage to pipe network, and

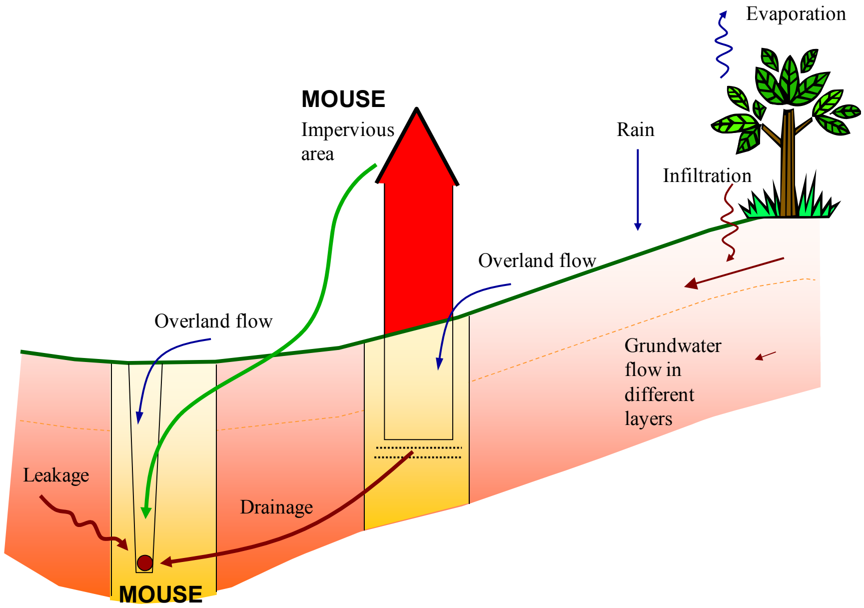

Figure 6: Principles behind the MOUSE-SHE coupling.

level and flows in water courses and sewer pipes. Figure 6 illustrates the comprehensive principles of the MOUSE-SHE system.

RESULTS

CALIBRATION

To be able to use the model setup in a credible way there is a need for calibration. In the calibration process simulated values are compared with corresponding measured values and different calibration parameters are used for tuning. In this type of model it is mainly the flows in the sewer network and the groundwater levels that are checked, both in terms of temporal distribution and the spatial distribution between different parts of the sewer network and the catchment area. The temporal distribution is important to describe accurately to be able to understand the governing processes and the causes for the variation. The spatial distribution is important to describe accurately so that the proposed measures are located in the right place and the likely effects of the measures can be assessed.

The parameters that have been adjusted in the model to achieve a good fit between measured and simulated values are:

- the leakage coefficient for sewer pipes in different sub-areas
- the hydraulic conductivity for different soil layers
- the retention curve and effective porosity for unsaturated conditions in the upper soil layers.

The calibration process revealed some interesting information. For some sub-areas (see red areas in Figure 4 and 5) the measured momentary flow is so large that it cannot be explained by the hydrological processes, *i.e.* the flow volume exceeds the amount of water that can be generated by rainfall in the area. The missing volumes are also relatively constant in time and does not vary with wet or dry periods. So there must be a different kind of source. A plausible explanation could be leakage from the water distribution network. The missing flow accounts for about 16 l/s which can be compared with the total measured momentary flow of 62 l/s in December 2008. Stockholm Vatten will investigate this matter further.

Figure 7 shows the calibration results for one of the gauged locations. In general, the model gives a good description of the flow distribution in the catchment and the typical temporal distribution. That the distribution of flow between the different measured locations has a good fit is a sign that the calibration of the leakage coefficients has been successful and in turn means that the most important differences in pipe conditions have been captured. That the temporal distribution of the simulated hydrograph has a good fit compared with measured data is a sign that the most important geohydrological processes have been described and that the contribution from foundation drains is in the right order of magnitude.

In Figure 8 the agreement between simulated and measured momentary flows during night time for all sub-areas is shown. The model gives a good description regarding the general distribution of leakage into pipes in the catchment, even if some local discrepancies are apparent.

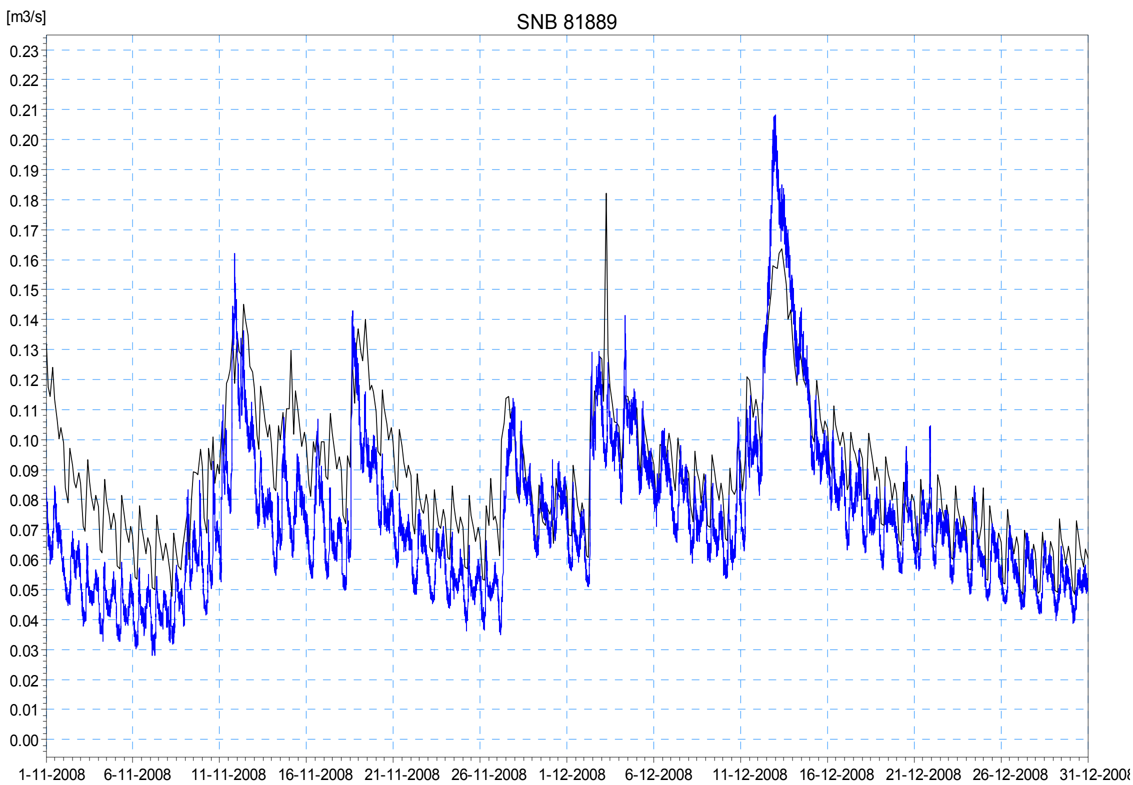

Figure 7: Comparison of simulated (black) vs. measured (blue) flow for the manhole SNB81889, approximately located in the middle of the catchment.

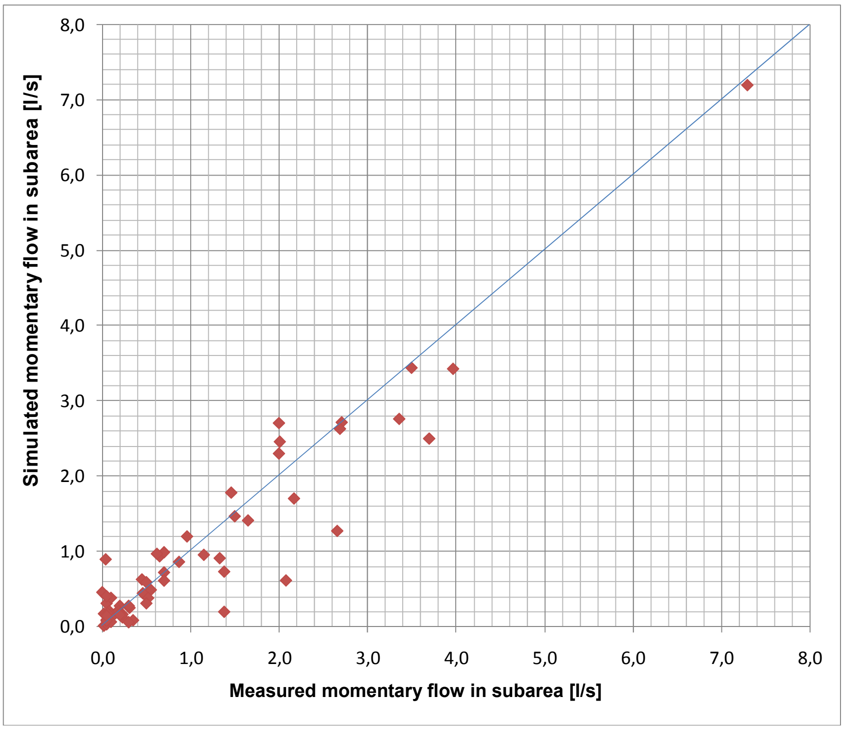

Figure 8: Comparison between simulated and measured momentary night flows in the sub-areas measured in December 2008.

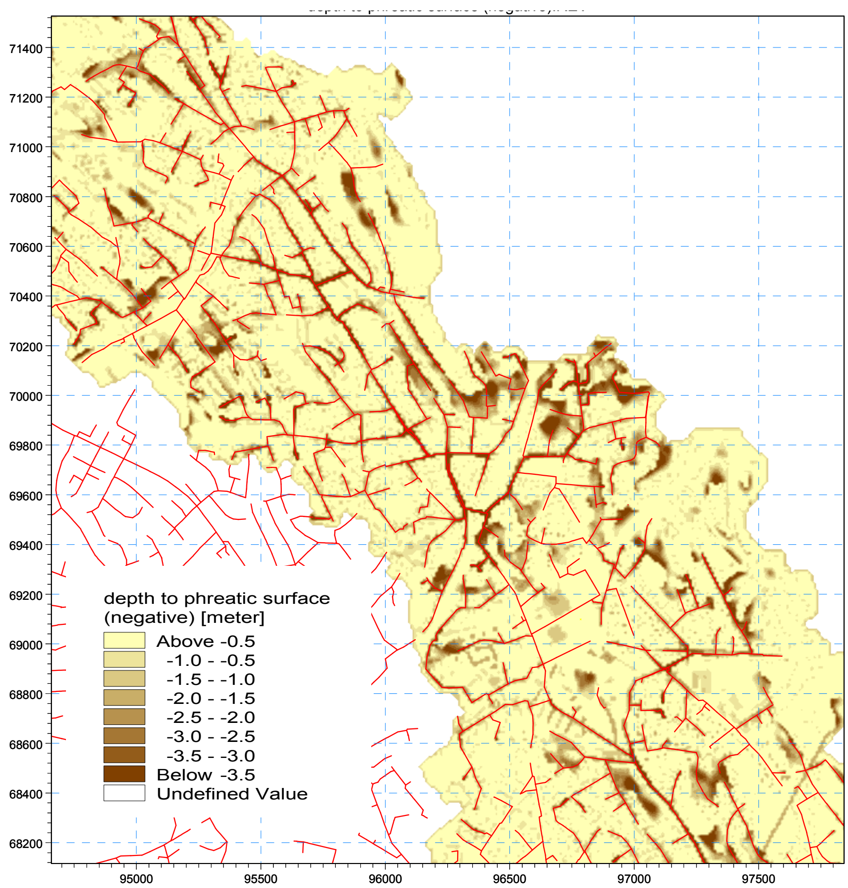

Figure 9: Simulated groundwater depth on the 15th of December 2008.

Figure 9 shows the simulated groundwater depth on the 15th of December 2008, approximately the same time as the momentary flow measurements were performed. It is obvious that the groundwater table is very close to the surface. With the exception of some areas on higher ground it is mainly along the sewer pipes and locally around buildings with basements where the groundwater table is lower as a result of the leakage into pipes and the foundation drains. This is also supported by the observations of groundwater levels in the catchment.

PRESENT CONDITIONS

To be able to describe the present conditions and later on the effects of RDII reducing measures, the northern part of the catchment has been divided in three sub-areas and the southern part has also been divided in three sub-areas, see Figure 10. The simulated hydrographs from the different sub-areas are shown in Figure 11 and 12.

From Figures 11 and 12 it is seen that the variation of flows is largest in the northern part of the catchment. The highest flow peaks originate from the sub-areas in northeast (A) and northwest (C). This is due to dramatic topography with large variations in elevation, and the large proportion of visible bedrock and thin or no soil cover. The opposite conditions apply in the southern area that is more flat and also has a large proportion of clay soil layer.

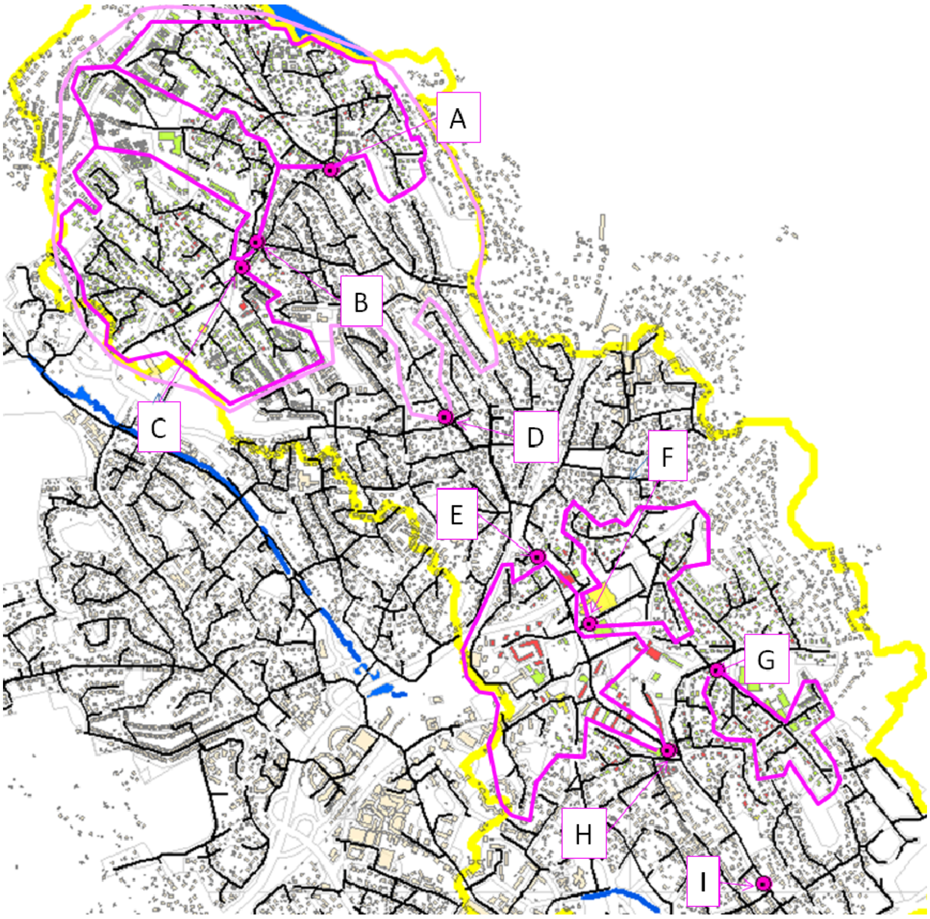

Figure 10: The six prioritised sub-areas (A,B,C,F,G,H) for studying RDII reducing measures.

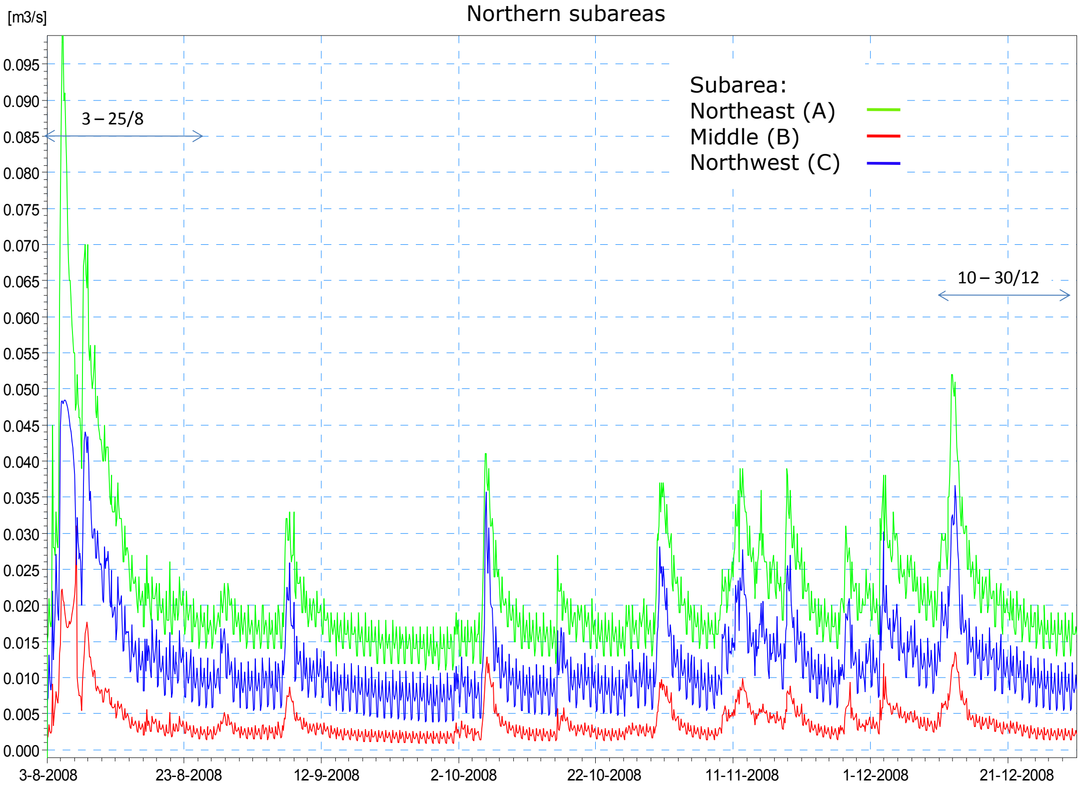

Figure 11: Simulated flow variation in autumn 2008 in the northern part of the catchment for each of the sub-areas in Figure 10.

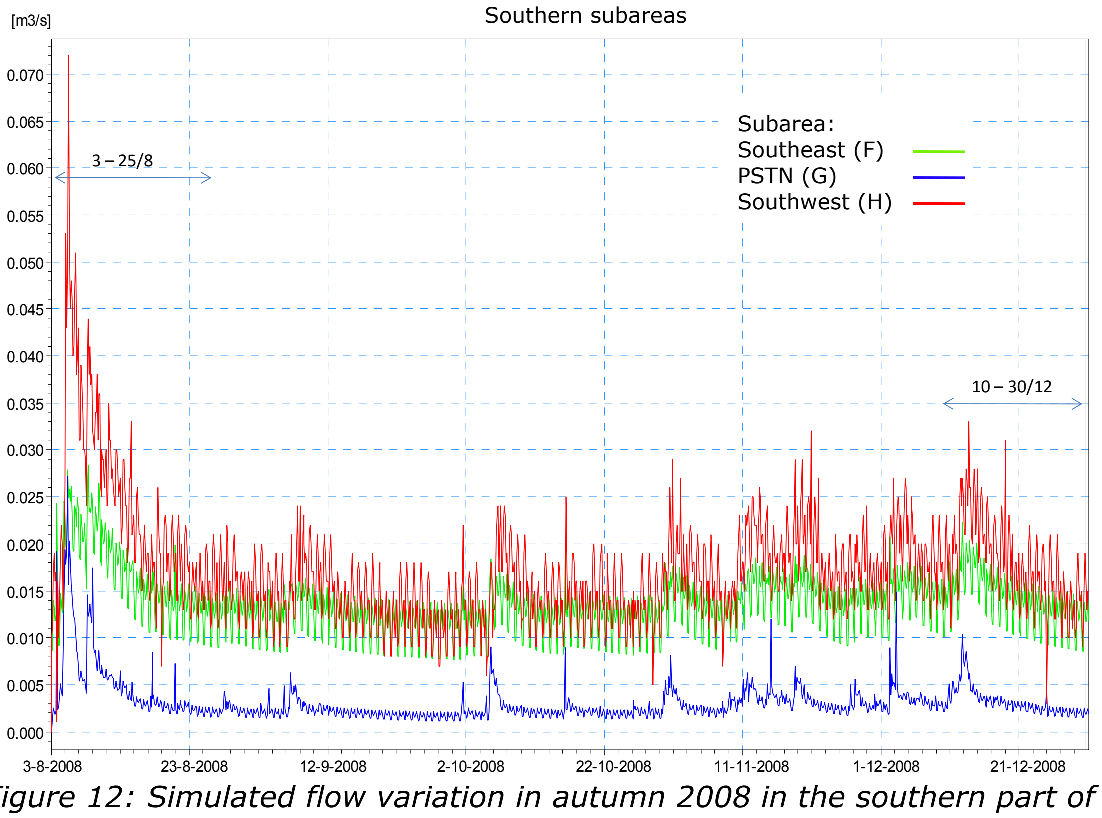

Figure 12: Simulated flow variation in autumn 2008 in the southern part of the catchment for each of the sub-areas in Figure 10.

The variation in flow that is seen in each sub-area can mainly be derived from leakage into sewer pipes and flows from foundation drains. The variation in flow is not especially influenced by connected impervious area, which is found to be about 4 hectares in total for the prioritised sub-areas (earlier calibrated in the MIKE URBAN model).

In the northern part the variation in flow is also accentuated by the fact that the stormwater runoff from most streets in the area have a limited, or non-existing connection with gully pots and ditches.

The estimated sewer volume contribution from different flow components for the six sub-areas is shown in Figure 13 and 14. This is calculated as the mean from two simulated periods: 3-25 august 2008 and 10-30 December 2008 (see time markings in Figure 11 and 12). As shown in the figures the leakage into the sewer pipes is a significant part of the overall conveyed volume. In the northern part foundation drains also contribute with a considerable part, about 25% of total volume while this part is only about 8% in the southern part.

The largest volumes of RDII into sewer pipes are found in the northeast sub-area (A), but also the northwest (C), southeast (F) and southwest (H) sub-area contribute with relatively large volumes.

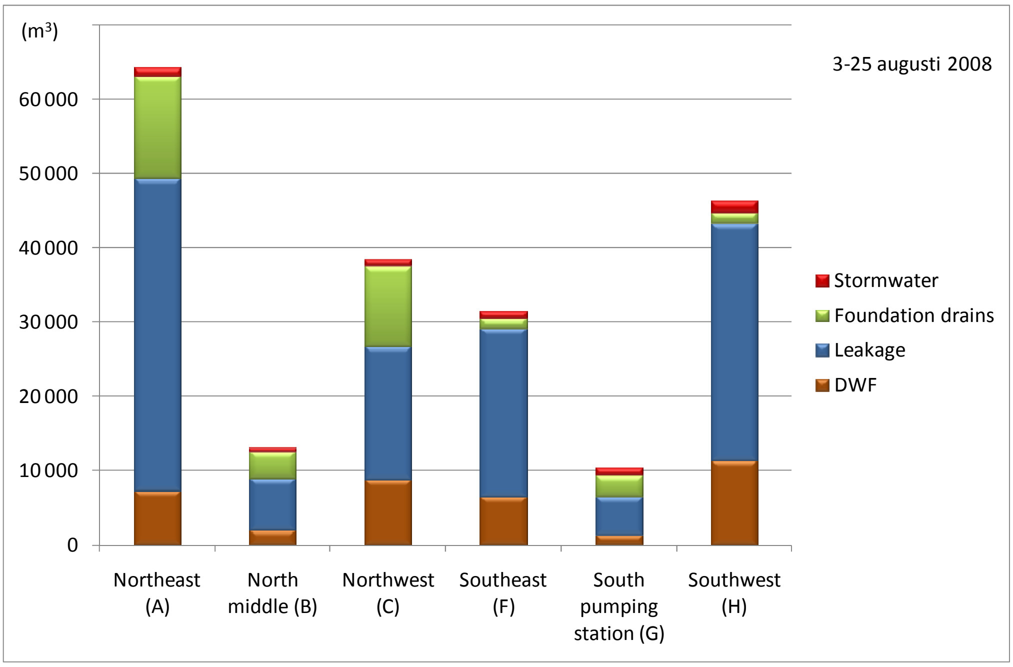

Figure 13: Simulated sewer volume from different flow components for the six sub-areas during the period 3-25 August 2008 (the period is marked in Figure 11 and 12).

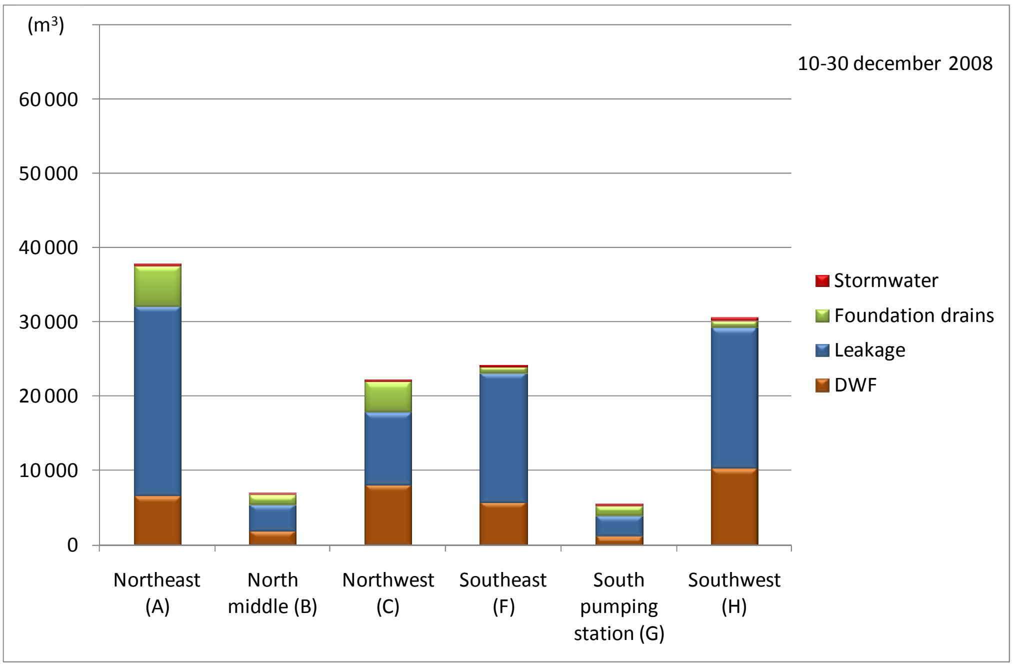

Figure 14: Simulated sewer volume from different flow components for the six sub-areas during the period 10-30 December 2008 (the period is marked in Figure 11 and 12).

PROPOSED MEASURES

The proposed measures comprise sealing of pipes and manholes in certain prioritised sub-areas and measures to improve the street runoff for a number of identified streets in the northern part of the catchment. In some sub-areas the simulation results for the sealing measures will show a negative effect on the RDII volume because of an increase in flows from foundation drains. Sealing measures, *e.g.* relining, are nevertheless motivated in these sub-areas because of the overall bad pipe conditions and other kind of problems can occur if the pipes are not rehabilitated. The proposed measures have been divided in three steps.

In the first step sealing of pipes and manholes is included within the sub-areas that according to measurements and simulations show the largest amount of inflow leakage per meter pipe. In practice this means the sub-areas that according to the momentary flow measurements have a Litre per Meter pipe and Day (LDM) larger than 200. The total pipe length within these sub-areas is about 7,200 meter. The sub-areas are shown in Figure 15. CCTV inspections of pipes in these areas show very bad conditions.

The second step of measures includes sealing of sewer pipes and manholes within certain sub-areas that have an LDM less than 200 but still according to measurements and simulations are showing a considerable amount of RDII. The sub-areas with measures according to step 2 are shown in Figure 16.

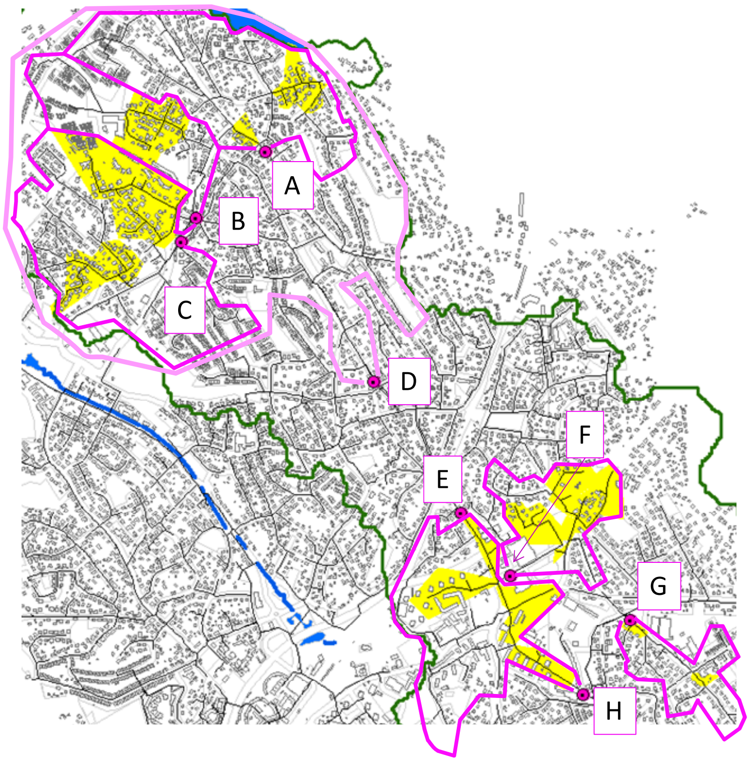

Figure 15: Proposed measures in step 1: relining of sewer pipes and manholes within the yellow areas.

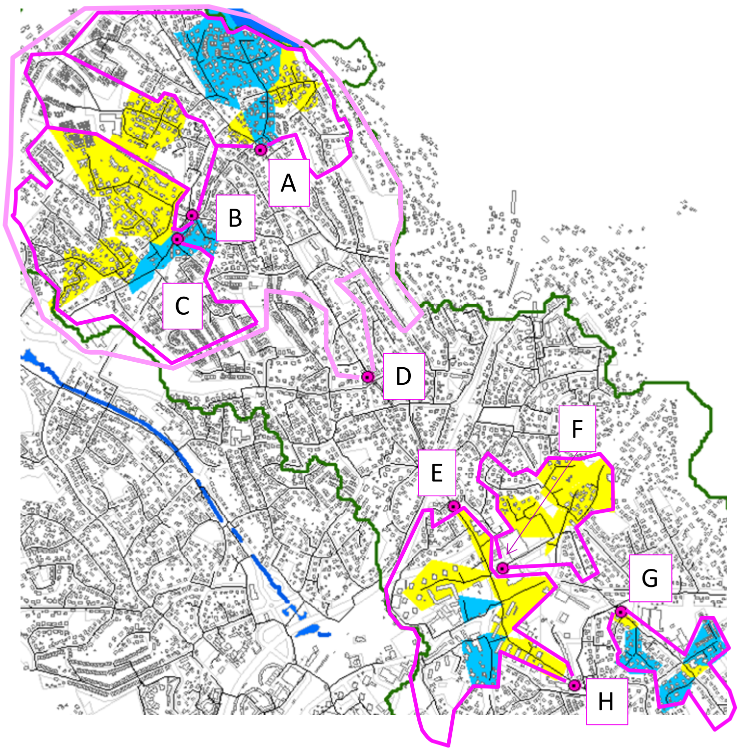

Figure 16: Proposed measures in step 2: relining of sewer pipes and manholes within the blue areas (proposed areas for measures in step 1 are marked yellow).

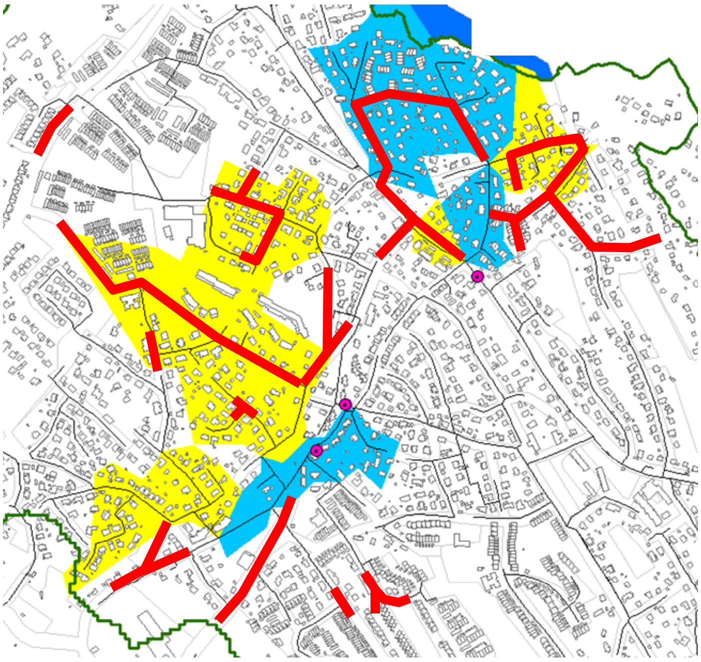

Figure 17: Proposed measures in step 3: more efficient street runoff conveyance along stretches marked with red (proposed areas for sealing measures in step 1 and 2 are marked yellow and blue, respectively).

The third step include measures for improving the runoff for a number of stretches of streets in the northern part of the catchment. These stretches have been marked with red lines in Figure 17. The total length of stretches is about 3,700 meter. Along these stretches it has been assumed that gully pots and/or ditches can convey the total stormwater runoff so that it does not contribute to infiltration and groundwater recharge.

EFFECTS OF MEASURES ON RDII FLOWS AND VOLUMES IN THE SEWER NETWORK

The proposed measures have been simulated step-wised in MOUSE-SHE and the results for the calculated reduction of RDII volume are shown in Tables 1 and 2. The simulations were made for two periods: a period in August 2008 with intensive rainfall and a period in December 2008 with wet hydrological conditions (the periods are also marked in Figure 11 and 12).

From the measures included in step 1 the largest RDII reduction is found in the southeast sub-area (F), then follows the middle (B) and the southwest (H) sub-area. The average total RDII reduction from measures in step 1 is about 40%.

The measures in step 2 do not give as good effect as the measures in step 1. The largest RDII reduction of 5% can be seen for the northeast sub-area. Considering the total length of pipes that needs to be relined in this area to achieve such a small effect, the cost benefit is much lower compared with the measures in step 1. The reason for this limited net effect in the northeast sub-area is that the groundwater table is elevated locally and the only possible outflow is through foundations drains which results in increased flows from the drains.

Table 1: Simulated RDII volume during the period 3-25 August 2008 for present conditions and for each step of measures. The reduction is presented for each measure.

3 - 25/8 2008							
	Present	Measure: Step 1		Measure: Step 2		Measure: Step 3	
	RDII	Reduction		Reduction		Reduction	
Northern area	[m3]	[m3]	[%]	[m3]	[%]	[m3]	[%]
Northeast - A	57,739	15,564	27%	3,100	5%	5,500	10%
Middle - B	11,070	5,700	51%			400	4%
Northwest - C	29,850	11,600	39%	0	0%	1,700	6%
Southern area							
Southeast - F	25,332	19,200	76%				
Pumping station - G	8,848	900	10%	0	0%		
Southwest - H	35,069	13,000	37%	700	2%		

Table 2: Simulated RDII volume during the period 10-30 December 2008 for present conditions and for each step of measures. The reduction is presented individually for each measure.

10 - 30/12 2008							
	Present	Measure: Step 1		Measure: Step 2		Measure: Step 3	
	RDII	Reduction		Reduction		Reduction	
Northern area	[m3]	[m3]	[%]	[m3]	[%]	[m3]	[%]
Northeast - A	32,072	11,228	35%	500	2%	3,100	10%
Middle - B	4,964	2,400	48%			300	6%
Northwest - C	14,364	4,500	31%	0	0%	1,300	9%
Southern area							
Southeast - F	18,520	13,000	70%				
Pumping station - G	4,280	100	2%	200	5%		
Southwest - H	21,008	7,600	36%	0	0%		

A more efficient runoff conveyance of street runoff in the northern area (step 3) gives an additional average RDII reduction of about 5% of the total volume in the northern and southern area. The largest individual reduction of about 10% is found in the northeast (A) sub-area. This is also the case if the total stretch of streets within each sub-area is taken into account.

EFFECT OF MEASURES ON MAXIMUM LEVELS IN THE SEWER NETWORK

To study the effect of the different measures with respect to their influence on the levels in the sewer network four types of rainfall events were simulated and evaluated. First an historical rainfall event from the 5th of August 2008, which also gave the highest recorded levels in the sewers during the flow measurements. This specific day the recorded rainfall was about 65 mm and the preceding days about 30 mm. As a comparison, three design storms of type CDS were simulated and evaluated. Every design storm had a return period of 10 years, but duration varied as one hour, six hours and 24 hours.

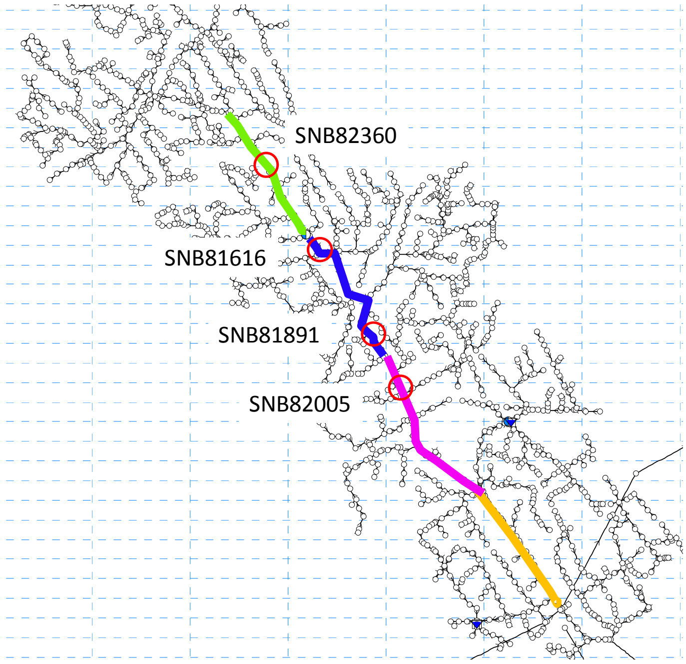

Figure 18: The critical locations for evaluation of maximum levels (red circles).

Table 3: Simulated maximum water levels above pipe ceiling for the critical locations shown in Figure 18.

	Simulated maximum level above pipe ceiling (m)			
	CDS-storm 1 tim	CDS-storm 6 tim	CDS-storm 24 tim	August 5 2008
Rain volume (mm)	23	38	57	67
SNB82005	0.54	0.54	0.46	1.10
SNB81891	0.32	0.32	0.52	1.42
SNB81616	1.41	1.38	1.21	1.71
SNB82360	0.44	0.54	0.98	1.64

Four critical locations in the sewer network were chosen for the evaluation process, see Figure 18. The total rainfall volumes for the four events, as well as the simulated maximum water levels above pipe ceiling are shown in Table 3 for the critical locations in Figure 18. For all locations it is the historical rainfall event from 5 August 2008 that gives the highest levels. The horizontal pressure profiles for this event have been evaluated. As an example, the horizontal pressure profile for the green stretch in Figure 18 including manhole SNB82360 is shown in Figure 19.

It can be seen in Figure 19 that the simulated pressure line exceeds the pipe ceiling with about 1-2 meter. This is also true for the blue pipe stretch in Figure 18. Further downstream along the pink pipe stretch the maximum pressure drops and is now about 0.5-1 meter above pipe ceiling, and for the yellow stretch (where the pipe diameter increases) the pipes are no longer pressurised.

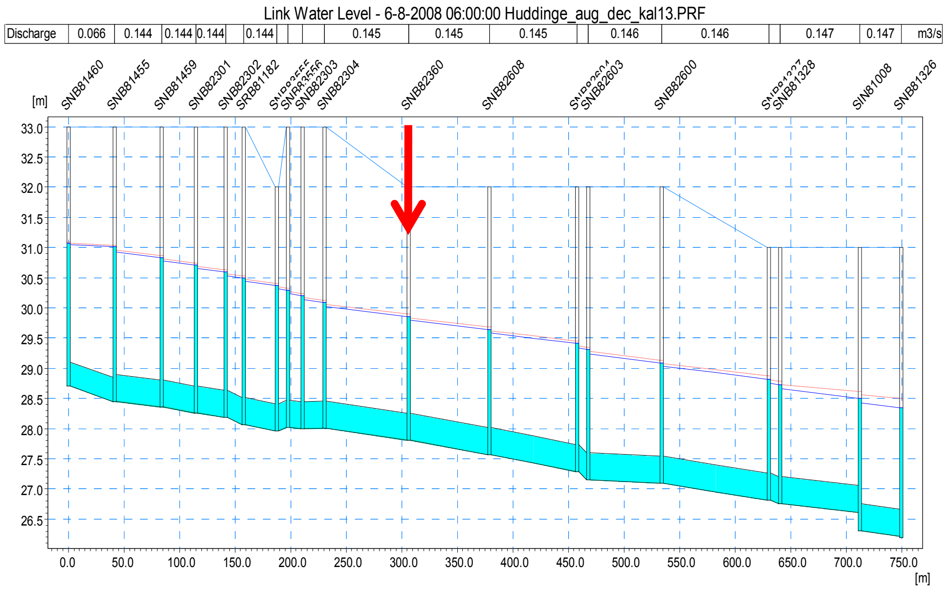

Figure 19: Simulated maximum pressure line for the green pipe stretch in Figure 18 (Red arrow shows the manhole SNB82360 that is shown in Table 3 and 4).

Table 4: Simulated maximum water levels above pipe ceiling for the rainfall event 5 August 2008 and for the critical locations shown in Figure 18. Simulations for the present system and the different steps of measures.

	Simulated maximum level above pipe ceiling (m)			
	Present system	Measures step 1	Measures step 1 & 2	Measures step 1, 2 & 3
SNB82005	1.10	0.83	0.75	0.72
SNB81891	1.42	1.22	1.16	1.12
SNB81616	1.71	1.62	1.55	1.49
SNB82360	1.64	1.34	1.28	1.01

Table 4 shows the effects on maximum water levels of the proposed measures for the rainfall event of 5 August 2008. The manhole which is located furthest upstream in the system (SNB82360) shows the largest level falling of about 60 cm for all measures included. With only Step 1 measures the falling is about 30 cm. For the three other manholes the effects on maximum levels are somewhat lower, about 20, 30 and 40 cm level falling respectively, with a higher effect more downstream. With only Step 1 measures the falling is about 10 cm less.

CONCLUSIONS

Coupled hydrological-hydraulic simulation of the catchment with the MOUSE-SHE system has been a vital part of the project. MOUSE-SHE modelling gave an understanding of the runoff and groundwater flows in the area. With the simulations it was possible to assess which pipes and subareas that yielded the largest amount of RDII. The model concept also made it possible to separate the RDII that originates from direct leakage to pipes from that of inflow from drainage of foundations and service pipes.

Furthermore, the model was used for assessing the effects of proposed measures comprised sealing of pipes and manholes in prioritized subareas together with measures for improving the stormwater runoff from certain streets. Simulation results of the sealing of pipes and manholes showed a 40% reduction of RDII volume, and improved stormwater runoff from streets reduced the RDII volume an additional 5-10%.

This project has given the client Stockholm Vatten concrete decision support in terms of a proposal of measures and their prioritisation with the aim of alleviating the problems with flooding of basements in the sanitary sewer system in Huddinge.

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