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Adaptation to climate change impacts on urban storm water: a case study in Arvika, Sweden

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Abstract Already today, the functionality of many sewer and storm water systems are not up to the required standards and consequently flooding problems are experienced in case of heavy storms. System upgrades are required, which are however complicated by the expected future increase in short-term rainfall intensities as a result of climate change. In this case study, focusing on the town of Arvika, Sweden, this issue is investigated in three main steps. In the first, extreme value analyses of 30-min rainfall from an ensemble of climate projections are carried out to estimate the future increase and generate a future design storm. In the second, the existing system's response to both today's and future design storms are simulated by a coarse sewer model setup (MOUSE) and a detailed coupled surface-sewer model setup (TSR). In the third and final step, system upgrades are designed and evaluated by both models. The results indicate an increase by 10–30 % of today's short-term rainfall extremes by the end of the century. Upgrading the system to achieve a satisfactory performance for the future design storm would cost approximately twice as much as an upgrade based on today's design storm.

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1 Introduction

Based on theoretical reasoning, a general expected consequence of climate change is an increase of extreme short-term rainfall intensities (e.g. Trenberth et al. 2003). A number of studies have analyzed short-term extremes in observed high-resolution rainfall time series to find out whether such an increase is already noticeable (e.g. Pagliara et al. 1998; Vaes et al. 2002; Arnbjerg-Nielsen 2006; Bengtsson and Milotti 2008; De Toffol et al. 2009). In some cases trends are found but often no trends are found and a recurring conclusion is that it is very difficult to draw any clear conclusion about trends because of short series and large variability. It may however be remarked that when trends are found these are far more often increasing than decreasing, which weakly supports the theoretical hypothesis of an increase.

Concerning future climate model projections, rather few analyses have yet been performed on the hourly or smaller time scales relevant for short-term rainfall intensities. The general conclusion from these efforts is however more unified than from the trend analyses; short-term extremes will most probably increase in the future. Grum et al. (2006) found that return periods for short-term rainfall extremes in Denmark will be approximately halved by the end of this century. Other investigations focused on Scandinavia confirm an increase, with from a few up to 50 % or more in terms of extreme intensities (e.g. Olsson et al. 2009; Onof and Arnbjerg-Nielsen 2009). Larsen et al. (2009) considered entire Europe and found increased extremes everywhere, although a smaller increase in the south than in the north. It should be emphasized that these results are associated with large uncertainties, both because the limited accuracy with which climate models describe short-term rainfall (e.g. Hanel and Buishand 2010) and the limited number of climate projections considered.

Despite the apparent uncertainties, it is clearly possible that extreme short-term rainfall intensities will increase in the future, perhaps substantially, which will then in turn affect society in different ways. A very direct consequence would be an increased pressure on cities' sewer drainage systems, as demonstrated in several urban hydrological climate change impact studies (e.g. Semadeni-Davies et al. 2008; Olsson et al. 2009). Problems with efficient dewatering following heavy rainfall events are not uncommon already today, e.g. because of urbanization beyond the system capacity, system damages or misconstructions, and tougher demands on the required performance. Thus, sewer system upgrades are required in many cities, and a key issue in this situation is whether to take climate change into account and, if so, how.

In this paper, a case study focusing on sewer system upgrade in Arvika town, Sweden, is presented. The main novel aspects as compared with previous similar investigations are related to (1) the treatment of projected extreme short-term intensities and (2) the uncertainty assessment. Concerning (1), the results from a formal extreme value analysis is transferred onto a design storm to generate the drainage system model input. Concerning (2), besides using a range of climate models representing different uncertainty aspects, two different drainage system models are used in order to assess also this type of uncertainty. Concrete adaptation measures are evaluated in both functional and economical terms.

2 Catchment and models

The Palmviken catchment is located in the central parts of Arvika town, western Sweden (Fig. 1). Arvika is in turn located at the shores of Kyrkviken bay, which is connected with lake Glafsfjorden through a narrow strait. Glafsfjorden is a part of the Byälven river catchment out of which 30 % is located in Norway and which drains to lake Vänern.

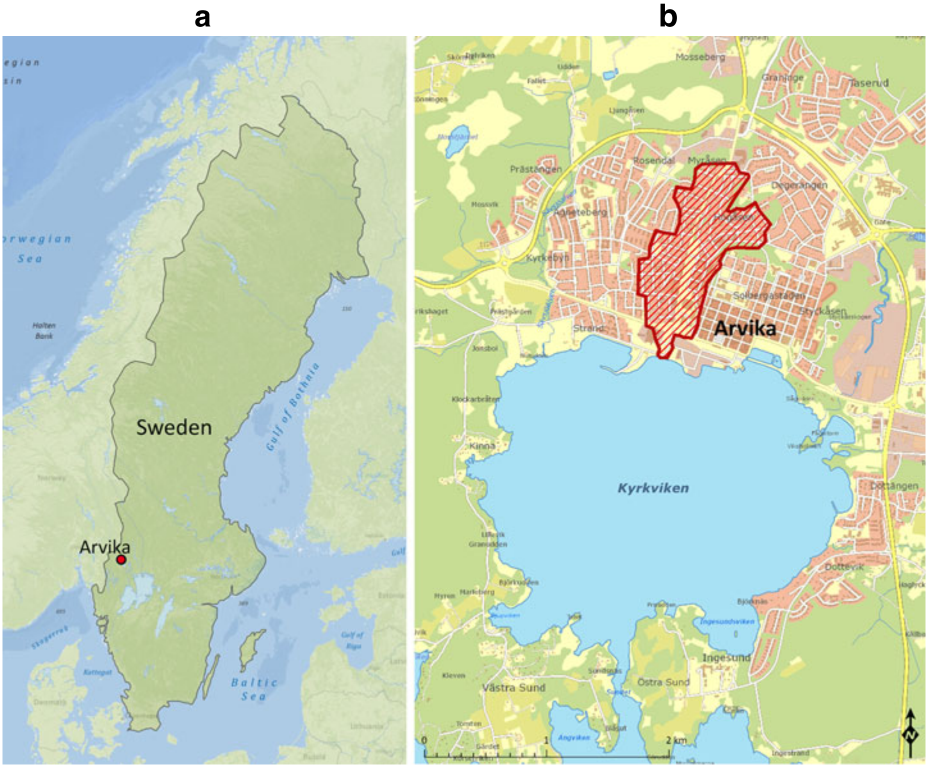


Fig. 1 The location of Arvika town in western Sweden (**a**) and Palmviken catchment (**b**)

Most of the ~1 km² big catchment slopes towards Kyrkviken, but the lower parts are flat. The catchment is mainly residential with both detached houses and apartment complexes, but the lower parts contain shops, a bus station and large parking areas. Railway runs in parallel to the Kyrkviken shore and crosses the southern part of the catchment. A green area exists in the central part of the catchment, but as it is located between two major roads it is used for recreational purposes only to a limited extent.

The sewer system is separated with different pipes for storm runoff and sewage, respectively, and is regularly flooded. Sometimes flooding is triggered by a high water level in Kyrkviken; a notable such case occurred in winter 2000. After several months of unusually large rainfall amounts the level in Kyrkviken exceeded the mean level by 3 m and large parts of central Arvika became inundated. More frequent is however flooding caused by heavy storms during summer. Besides creating potential problems for transport and communication, a notable consequence of these storm-related events is that basements become inundated; more than 20 such events have occurred only in the last 5 years. The problems are partly related to a poor condition of the sewage pipes, which allows both ground- and storm water to enter the system and flow backwards into basements, but also an insufficient capacity of the storm water system (see further section 4 below). If it can be shown that the inundation was caused by insufficient performance of the sewer system, the municipality is required to compensate for the damage which may be costly. Further, such legal processes puts a heavy workload on the municipality as it is responsible for the technical investigation.

In light of these recurring problems, Arvika municipality is currently considering ways to improve performance of the system, taking climate change into account.

2.1 Storm water system modeling

To model the storm water system's response to a heavy rainfall event, the system and the catchment were set up using two models: MOUSE and Tokyo Storm Runoff (TSR) model. MOUSE is an established sewer pipe flow model which has been widely used in many parts of the world and is today succeeded by MIKE Urban (http://mikebydhi.com/Products/Cities/MIKEURBAN.aspx). The TSR model is relatively new and described further below. Model calibration to observed runoff was not attainable due to lack of data.

In the MOUSE set-up, the storm water system is made up by 245 nodes and 245 pipes, neglecting small peripheral pipes. The nodes are assumed not to have any limitation with respect to inflow, i.e. an infinite capacity. At surcharged conditions, a node act as a sink and the surcharged water is removed from the system. The pipes are considered fully functional without any sediment deposits, cracks, etc., thus no leakage into or out from the pipes is assumed. Concerning the catchment surface, 41 % is considered entirely impermeable and 33 % to have a limited permeability. The runoff coefficients used was 0.9 for roofs, 0.8 for asphalt and 0.4 for gravel. A mean water level is assumed in Kyrkviken, corresponding to +45.7 m.a.s.l., which is justified by the fact that the highest rainfall events occur in summer when the water level is average or below.

The TSR model is a rainfall-runoff model for urban environments based on "urban landscape GIS delineation", by which all flow paths in an urban catchment can be represented with a very high level of detail (Amaguchi et al. 2012). Water flows on the ground surface and in the sewer system, respectively, are fully coupled, allowing dynamical simulation of surcharge and inundation events. The main novelty of this approach is that GIS is used in a more flexible way than in previous approaches, to allow for a more detailed representation of not only the urban catchment but also the storm runoff process from individual buildings and blocks, through roads and/or sewer system, to the receiving river in a physical and explicit way. In the standard formulation of the TSR model all flow calculations are based on established hydrologic and hydraulic concepts and equations, which can however be replaced by other formulations. Surface flows as well as river and sewer flows are simulated by unsteady flow equation. As flow is calculated for single segments, a one-dimensional formulation is sufficient. A key advantage of the TSR model, and the urban landscape GIS delineation, is the ability to accurately include and evaluate existing or planned flood-preventing structures in a straight-forward and explicit way.

For the TSR model set-up in Arvika, general GIS-based land-use information was combined with aerial photographs, high-resolution DEM (obtained by laser-scanning) and a network map of the main sewer pipes. Some manual processing was required, e.g. segmentation of roads and addition of minor pipe branches (the final TSR pipe network contains 1 838 nodes and 1 838 pipes). The delineation produced a total of over 18 000 homogeneous elements that were finally combined and hydraulically connected to completely specify the small urban catchment (Fig. 2). As parameter calibration was unattainable, standard values were used for initial loss, infiltration capacity and roughness coefficients (e.g. Ando et al. 1986; Yen 1991; Van de Ven et al. 1992). The runoff ratio was set to 0.7 and Hortonian infiltration was assumed.

According to Swedish design guidelines, the sewer system in Palmviken should be dimensioned so that (1) the water level resulting from a 1-year rainfall does not anywhere reach above pipe top and (2) the water level resulting from a 10-year rainfall does not

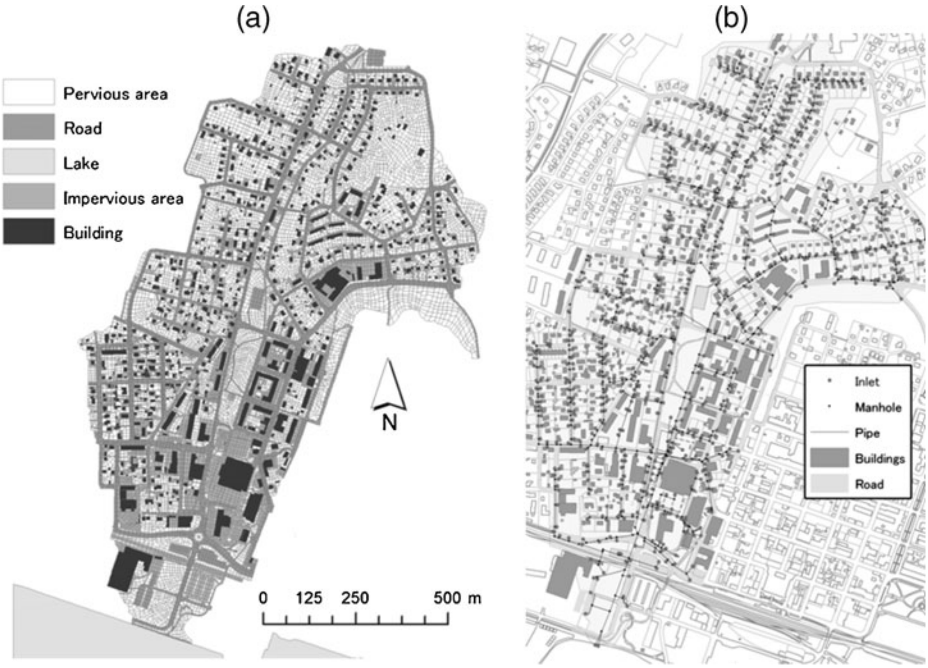


Fig. 2 Final maps of overland component (**a**) and sewer element with road and buildings (**b**) in the Palmviken catchment, as represented in the TSR model

anywhere reach above ground surface or basement elevation (Svenskt Vatten 2004). From preliminary simulations, case (2) was found to be decisive in Palmviken, thus the following analysis and modeling focuses on the 10-year rainfall.

3 Climate projections of extreme short-term precipitation

To assess the climate change impact on short-term precipitation extremes, an ensemble of six climate projections for the period 1961–2100 were analyzed (Table 1). All General Circulation Model (GCM) projections were dynamically downscaled over Europe to 50×50 km resolution by the Regional Climate Model (RCM) RCA3 (Kjellström et al. 2005). The

Table 1 Climate projections used in this study

Denotation	General circulation model (institute)	IPCC	Member
E4_A2	ECHAM4 (Max Planck Inst.)	A2	–
E4_B2	ECHAM4 (Max Planck Inst.)	B2	–
E5_A1B_1	ECHAM5 (Max Planck Inst.)	A1B	1
E5_A1B_2	ECHAM5 (Max Planck Inst.)	A1B	2
E5_A1B_3	ECHAM5 (Max Planck Inst.)	A1B	3
HC_A1B	HadCM3 (Hadley Centre)	A1B	–

ensemble contains three GCMs (including two versions of the same model, ECHAM), three IPCC SRES scenarios and three model initialization members. The SRES scenarios represent the uncertainty related to the future global development in terms of population, technology and socio-economy (Nakićenović et al. 2000). The members represent the uncertainty related to the projections' initial conditions and in turn reproduction of low-frequency climate oscillations.

It should be emphasized that precipitation at the RCM grid scale (50×50 km) is used to estimate future changes at the local scale. This requires an assumption that grid-scale changes are representative also at the local (i.e. point) scale. This is not certain, as different rainfall generating mechanisms come into play at different scales. Whereas point-scale extremes are virtually always generated by localized convective cells, below the scale of the RCM resolution, grid-scale extremes may also be caused by heavy large-scale rainfalls. It has been indicated that the future point-scale increase may be slightly higher than the grid-scale increase, but for practical applications the latter may be used as a conservative estimate (e.g. Olsson et al. 2011).

From all projections, time series of 30-min precipitation intensities from a matrix of 3×3 RCA3 grid boxes, centered over Arvika, were extracted for two 30-year periods: 1961–1990 (reference; REF) and 2071–2100 (end of century; EoC). The reasons for choosing these particular periods were that (1) the rainfall statistics used for sewer system design and evaluation today are based on observations before 1990 and (2) the expected lifetime of new installations is 50–70 years, i.e. almost to the end of the century.

3.1 Extreme value analysis and rainfall input generation

As design and evaluation of the Palmviken catchment sewer system is based on a 1-hr rainfall event with a 10-year return period, the analyses focus on this event. From each of the 18 30-year time series (two periods from nine grid boxes), Gumbel (EV1) distributions were fitted to annual maxima for durations 30 min and 1 h and the 10-year values calculated. The choice of the Gumbel distribution is based on a national study of short-term precipitation extremes in regional climate projections where different distributions were evaluated (not shown). The Gumbel (EV1) distribution was found to provide a robust and accurate approximation. It may be remarked that the difference between different distributions is very small for low and intermediate return periods (e.g. 10 years).

For duration 30 min, in period REF the average 10-year intensity over all projections is 6.0 mm/hr, ranging from 5.6 mm/hr (E4_B2) to 6.6 mm/hr (E5_A1B_2) (Table 2). The standard deviation for each projection, which represents the variability between neighboring grid boxes, is on average 0.4 mm/hr (with little variation between the projections) which corresponds to ~7 % of the estimated 10-year intensity. In period EoC, the 10-year intensity ranges from 7.1 mm/hr(E4_B2) to 8.0 mm/hr (HC_A1B), being on average 7.4 mm/hr. The standard deviation is similar to period REF in absolute terms and thus slightly lower in relative terms, ~5 %. For duration 1 h, the average 10-year intensity is 4.5 mm/hr in period REF and 5.5 mm/hr in period EoC. The variation between projections is similar to duration 30 min. The standard deviation is slightly lower, being on average ~5 % in period REF and ~3 % in period EoC.

Concerning the increase of the 10-year 30-min rainfall intensity from REF to EoC, it varies between 8 % and 28 % in the projections, being on average 24 % (Table 2). The variation between neighboring grid boxes is substantially higher for the future increase than for the estimated intensities, ranging from 7 % to 18 % (percentage points) which

Table 2 Estimated 10-year intensities for durations 30 min and 1 h in periods REF and EoC, and the corresponding change, for all projections. The values are given as mean±standard deviation, where the latter represents the variability among the nine neighboring grid boxes used

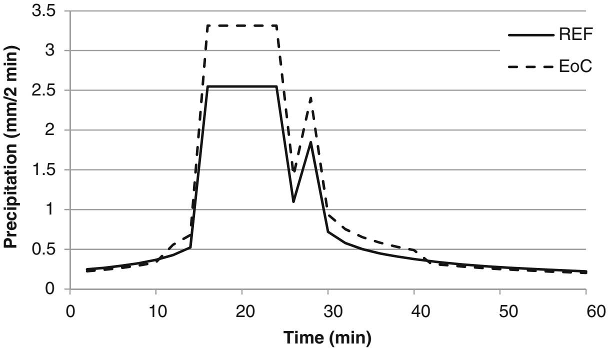
	10-year intensity: 30 min			10-year intensity: 1 h		
	REF (mm/hr)	EoC (mm/hr)	Change (%)	REF (mm/hr)	EoC (mm/hr)	Change (%)
E4_A2	5.7±0.4	7.3±0.3	27.9±11.2	4.3±0.2	5.9±0.2	34.5±10.3
E4_B2	5.6±0.7	7.1±0.3	24.7±18.4	4.4±0.2	5.4±0.1	24.7±6.2
E5_A1B_1	6.0±0.3	7.2±0.3	14.1±7.1	4.6±0.2	5.3±0.2	14.6±5.7
E5_A1B_2	6.6±0.4	7.3±0.5	7.6±9.3	4.8±0.2	5.4±0.1	11.8±5.8
E5_A1B_3	5.8±0.4	7.4±0.3	24.5±8.1	4.6±0.3	5.8±0.1	22.6±8.3
HC_A1B	6.3±0.4	8.0±0.5	27.8±10.8	4.5±0.3	5.4±0.2	25.6±8.9
Average	6.0±0.4	7.4±0.4	23.6±10.8	4.5±0.2	5.5±0.2	22.6±7.5

corresponds to nearly 50 % of the estimated change on average. For all projections, the future increase for duration 1 h is similar to the 30-min increase and thus also the average increase is similar, 23 %. The standard deviation is somewhat lower, being on average 35 % of the estimated change.

A notable aspect in Table 2 are the differences between the different initialization members E5_A1B_1, _2 and _3. The effect of initialization is generally most pronounced in the near future where members may differ substantially, reflecting natural climate variability. By the end of the century, however, they often converge as climate change then dominates over natural variability. In light of this, the differences found here are somewhat surprising, but on the other hand a large statistical scatter is expected in extreme value analyses of short-term precipitation.

To quantify the future change in the sewer system modeling, it was decided to use the mean future increase from Table 2. The sewer system model input was generated by re-scaling the existing design storm (Fig. 3). The re-scaling was performed by first increasing the central 30-min period of the design storm, between minutes 10 and 40, with the average 30-min increase (23.6 %). This requires an assumption that shorter-duration intensities will change similarly to the 30-min intensity. As the changes at 30-min and 1-hr durations are generally similar (Table 2), assuming a similar change also for shorter durations appears justified. Finally the remaining parts of the design storm were adjusted to make the total

Fig. 3 Existing (REF) and future (EoC) design storm used in the sewer system simulations



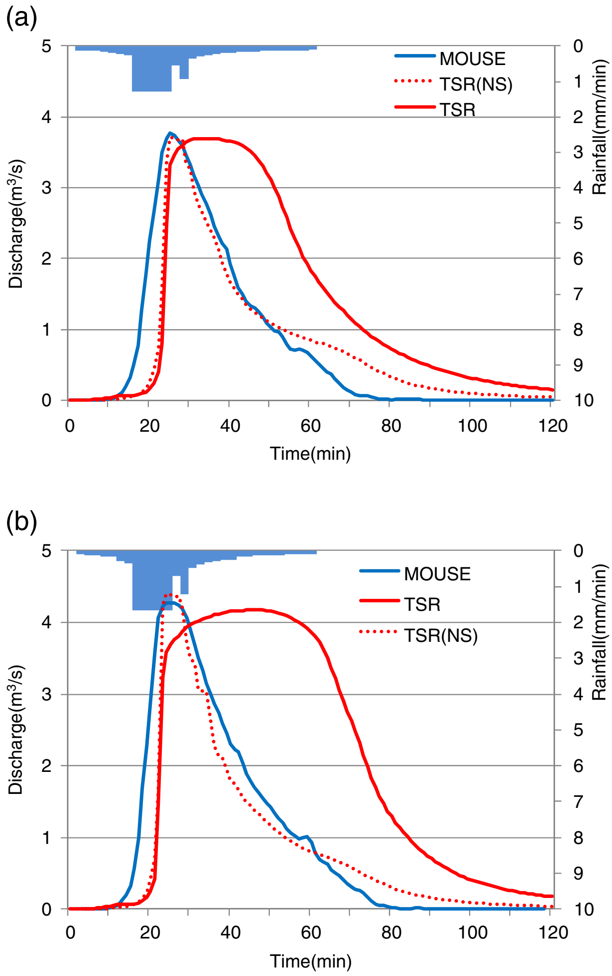


Fig. 4 Hydrographs in the catchment outlet simulated by MOUSE, TSR and TSR without surface model (TSR(NS)) for design storms REF (**a**) and EoC (**b**)

increase agree with the 1-hr increase (22.6 %). It may be remarked that the EoC design storm is similar to today's 20-year storm.

4 Performance of existing sewage system

In an attempt to make the TSR model comparable with MOUSE, its surface model was disconnected and thus it only simulated sewer pipe discharge; this model is denoted TSR (NS) where NS stands for Non-Surface. The results from design storm REF (Fig. 3) in MOUSE and TSR(NS) are overall similar, with a rapid discharge increase after some 10 min and an almost identical peak around 3.8 m^3/s after 25 min (Fig. 4a). The main difference is a somewhat delayed and steeper rising limb in the TSR(NS) model. This is likely because convective acceleration is neglected in the TSR model. Also in other respects the TSR sewer model is simplified compared with MOUSE, e.g. in terms of pipe segmentation and description of hydraulic losses, but these results indicate that the simplifications do not have a substantial negative impact on performance.

In the full TSR model, the rising limb of the hydrograph is identical to that obtained by the non-surface model (Fig. 4a). The peak discharge is slightly lower, delayed some 10 min and extended over a period of ~15 min, in sharp contrast to the distinct peak in the TSR(NS) model results. This difference illustrates the effect of the coupled surface model, with its overland routing of flooded water that eventually reaches the catchment outlet. The runoff ratio, calculated on basis of the 2-hr period shown in Fig. 4, in both MOUSE and TSR(NS) is 28 %, whereas it is 43 % in the full TSR model. Thus it is estimated that 15 % of the rainfall volume surcharges from the sewer system.

In the MOUSE simulations, the number of flooded manholes is 50 for design storm REF and these manholes are rather evenly spread out over the catchment area (Fig. 5a). The number of flooded manholes in the full TSR model simulation is lower, 33, and these manholes are further concentrated to three distinct locations (Fig. 5b). In particular, inundation occurs in the lower parts of the catchment's central green area. The pronounced difference in response between the two models are likely to a large extent related to the different level of detail used in the model set-ups. In the comparatively coarse MOUSE set-up, each manhole gets a large contributing area and in turn large and fast inflows at high rainfall intensities. By the more detailed set-up in the TSR model, in combination with the overland routing, the character of manhole inflows becomes less instantaneous. Further, the total sewer system volume is some 20 % higher in the TSR set-up.

Concerning the models' performance, it cannot be concluded that the result from one of the models is more realistic from that of the other. The southern of the three

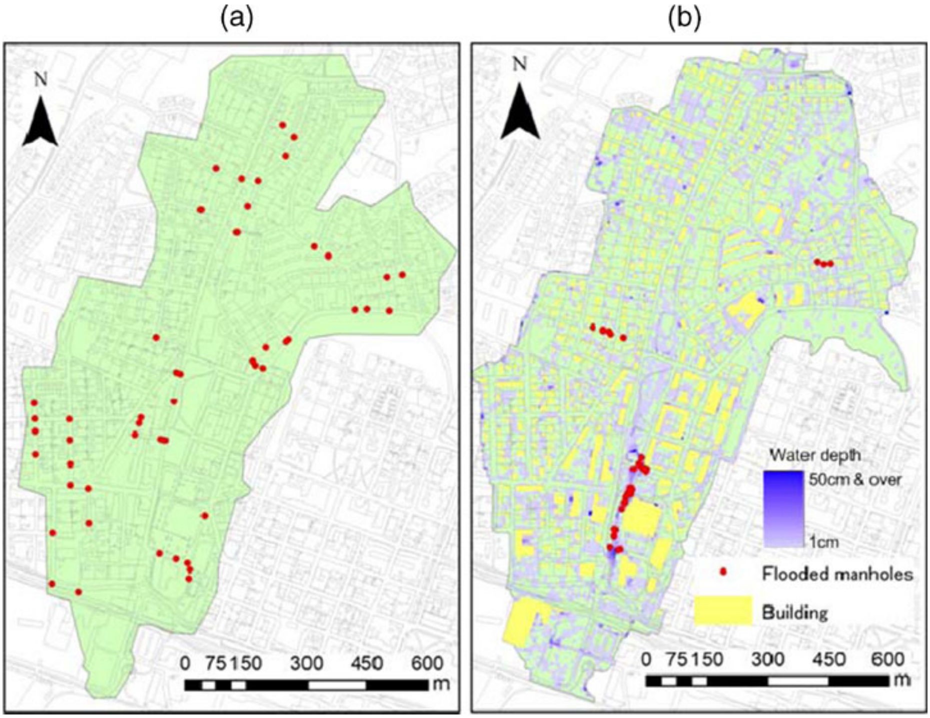


Fig. 5 Flooded manholes for design storm REF simulated by MOUSE (**a**) and TSR (**b**)

areas identified by the TSR model, in the central green area (Fig. 5b), is a known ‘problem area’ where flooding does occur. This area is less pronounced in the MOUSE results (Fig. 5a). On the other hand, by MOUSE another known problem area slightly north-west of the central one is identified, which does not show up in the TSR results. A more detailed performance assessment is difficult as (1) known problems may be related to unknown damages or misconstructions that cannot be modeled and (2) flooding may happen that is never reported and thus problem areas unknown to Arvika municipality may exist.

The results from applying design storm EoC (Fig. 3) to the existing system are principally similar. Peak discharge in the catchment outlet however increase by ~0.5 m³/s in all models (Fig. 4b). Runoff ratios for MOUSE and TSR(NS) are similar to the REF simulations, but the TSR ratio is now 50 %, indicating that ~20 % of the rainfall volume surcharges. As in the REF simulations, by MOUSE flooded manholes occur in all parts of the catchments whereas by TSR they are concentrated to three areas (Fig. 6). The number of flooded manholes is 92 in MOUSE and 69 in TSR.

The sewer system in Palmviken is thus not up to the required standards according to the current national guidelines. One reason is that guidelines have been changed; a large part of the system was designed according to older standards which required the system to handle a 2-year rainfall instead of today’s 10-year rainfall. Further, previous system upgrades have generally focused only on localized problematic areas, with little consideration about the total system function in the entire catchment.

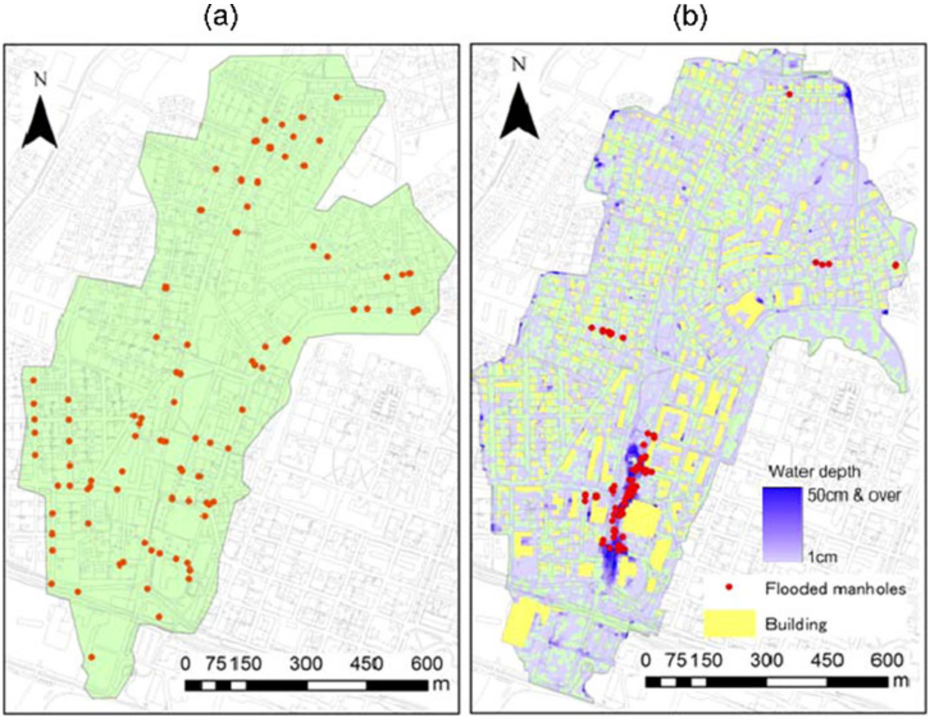


Fig. 6 Flooded manholes for design storm EoC simulated by MOUSE (**a**) and TSR (**b**)

5 Performance of sewage system after upgrade

Two main strategies exist with respect to flood prevention and control; subsurface- and surface-oriented. In the former the network capacity is increased, generally by replacing pipes limiting the discharge with larger-diameter ones or by installing subsurface storages. In surface-oriented solutions, open waters such as ponds or channels are constructed, in which storm water may be stored and delayed following heavy rainfall events. Generally, pipe replacement in an urban area is very costly. As a suitable green area available for construction of e.g. retention ponds further is available in Palmviken, a surface-oriented solution was believed to be the most cost-effective and preferred alternative.

Initial simulations to find an optimal adaptation plan with respect to cost-efficiency were made in MOUSE. Based on the results, a combined subsurface- and surface-oriented solution was selected, including both replacement of pipes and construction of retention ponds. Two alternatives were considered; one in which the system capacity is increased up to today's design standards (alt. 1) and one in which also the climate change impact is considered (alt. 2). The suggested locations of replaced pipes and retention ponds are shown in Fig. 7.

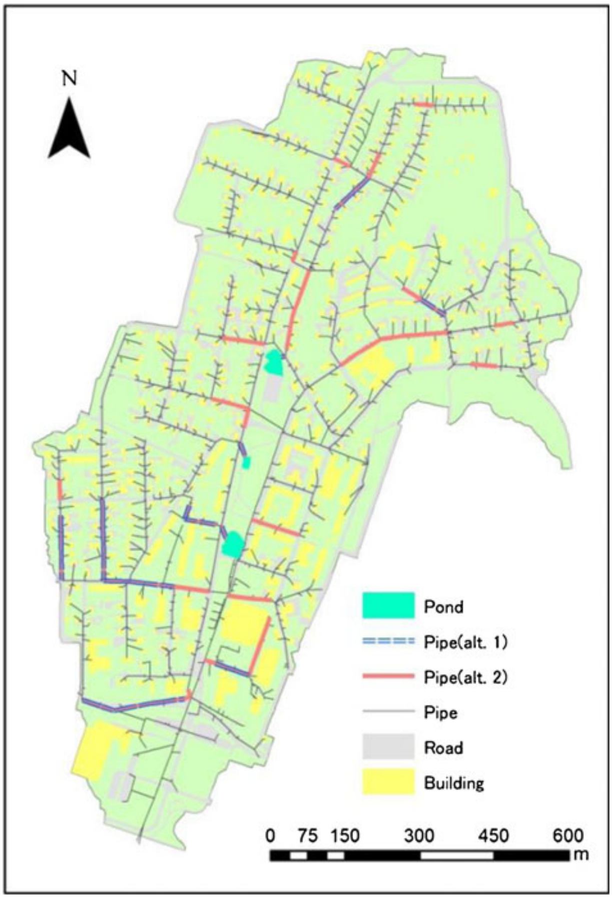


Fig. 7 Suggested plan for sewer upgrade. Pond locations are the same in both alternatives but pipe locations differ (alt. 1 and 2, respectively)

5.1 Alternative 1: system upgrade without climate change impact

In order to meet today's design standards, replacement of some 1,500 m of pipes and construction of three retention ponds with a total volume of 920 m^3 was suggested. The estimated cost is 4.75 million SEK (~515 000 EUR), calculated using standard Swedish guidelines (http://www.kpsystem.se/index.php). The ponds would be located in the essentially unused central green area (Fig. 7).

The simulation with design storm REF in MOUSE shows no impact on peak discharge in the catchment outlet, as compared with the response in today's existing system, but only a faster recession and a reduction of the runoff ratio from 28 % to 23 % (Fig. 8a). That the peak runoff does not decrease is likely because the limited capacity of the outlet pipe which makes it flow full also after the system upgrade. In MOUSE, the upgrade effectively means that some surcharged water from the upstream part of the catchment (Fig. 5) becomes stored in the ponds instead of being removed from the system, which has no impact on peak runoff because of the limited pipe capacity. The results from the full TSR model, however, indicate a slight decrease in peak discharge with ~0.3 m^3/s (Fig. 8a). This is likely caused by the fact that surcharge and

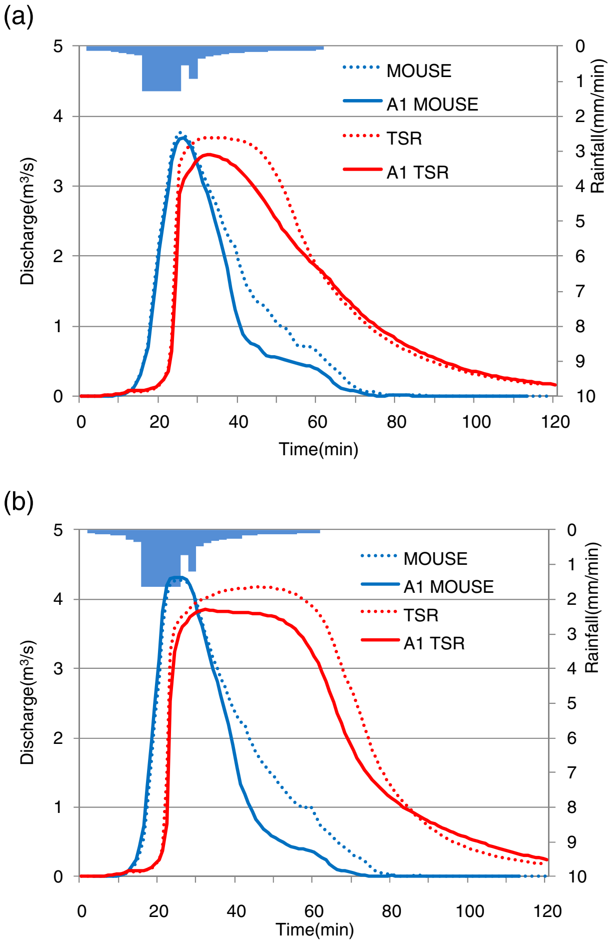


Fig. 8 Hydrographs in the catchment outlet before (*dotted lines*) and after (*solid lines*) system upgrade according to alternative 1 for design storms REF (**a**) and EoC (**b**)

inundation in the TSR model mainly takes place in the downstream, relatively flat part of the catchment (Fig. 5). Therefore peak runoff is related to the difference in water level between the inundated area and the lake. As this difference decreases after the upgrade, also the peak runoff decreases. In the TSR model, the runoff ratio decreases from 43 % to 40 %.

In the MOUSE simulation, only three manholes are flooded for design storm REF after upgrade according to alternative 1 (Fig. 9a). Despite the pronounced differences in the existing system's response to design storm REF in MOUSE and TSR, respectively (Fig. 5), the suggested adaptations appear satisfactory also when simulated by the TSR model. Only one flooded manhole remains, and the function of the retention ponds is verified in the TSR results (Fig. 9b).

An important issue is what may happen if the system is upgraded without taking the climate change impact into account (i.e. according to alternative 1), but that a change in rainfall extremes according to the scenarios considered here actually happens (i.e. a change to design storm EoC). The results in terms of outlet hydrographs are overall similar to the results from using design storm REF, in terms of changes in peak runoff and runoff ratio (Fig. 8b). In terms of flooding, 61 manholes are flooded in MOUSE and 38 in TSR. Both the numbers and the spatial distribution of these manholes are similar to what was found for design storm REF in today's existing system, i.e. in MOUSE they are spread out over the catchment and in TSR they are concentrated to three areas (Fig. 10).

5.2 Alternative 2: system upgrade with climate change impact

According to MOUSE simulations, making the system able to satisfactorily handle also the estimated 10-year rainfall by the end of the century would require an additional 1,500 m to

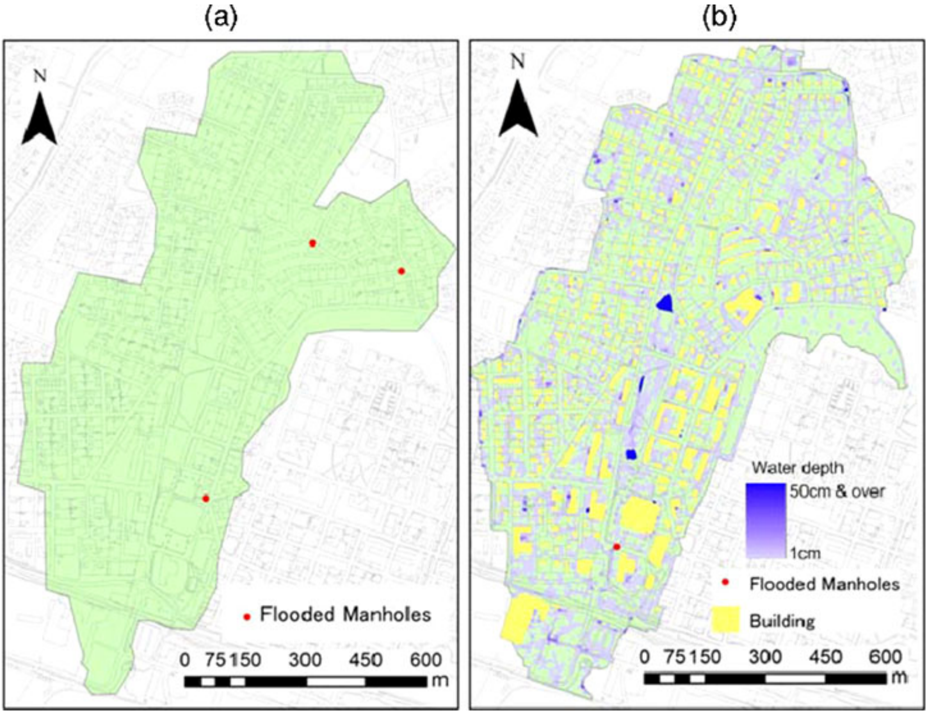


Fig. 9 As Fig. 5 but after system upgrade according to alternative 1

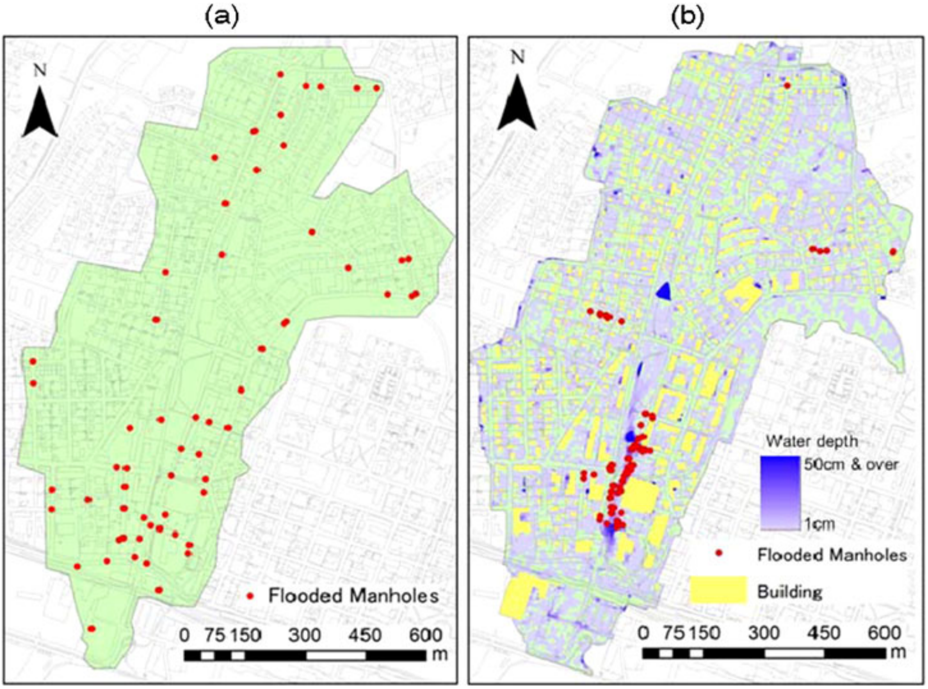


Fig. 10 As Fig. 6 but after system upgrade according to alternative 1

be replaced and a total pond volume of 1,810 m³, approximately doubling the costs involved to 9,4 million SEK (~1 million EUR). The impacts of alternative 2 on the catchment outlet hydrographs in response to design storm EoC (Fig. 11) are principally very similar to the impacts of alternative 1, discussed in connection with Fig. 8.

In the MOUSE simulations, 10 flooded manholes remain after alternative 2 (Fig. 12a) which was considered satisfactory. In the TSR results 22 flooded manholes remain, concentrated to two of the three problem areas found in previous simulations (Fig. 12b). The

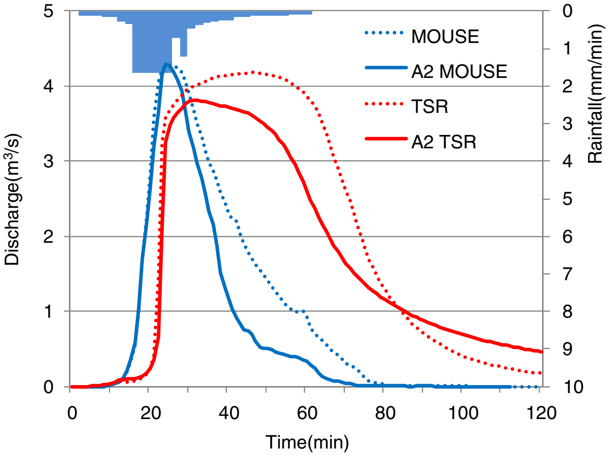


Fig. 11 Hydrographs in the catchment outlet before (*dotted lines*) and after (*solid lines*) system upgrade according to alternative 2 for design storm EoC

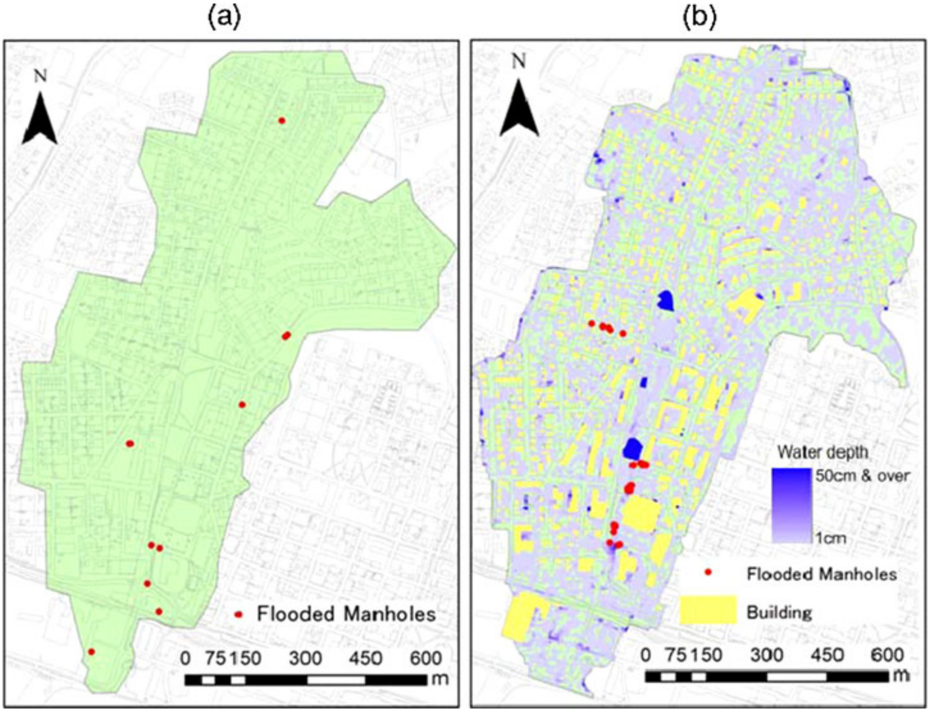


Fig. 12 As Fig. 6 but after system upgrade according to alternative 2

maximum inundation depth is ~15 cm, just after the flooded manhole furthest downstream. An analysis of the simulation suggests that some additional adaptation would be recommended to reach a proper system functionality also in response to design storm EoC. This could include e.g. a further increase of the pipe diameter in the western problem area and an increased volume of the southern retention pond.

6 Summary, conclusions and discussion

- Storm runoff modeling by MOUSE and TSR shows that the storm water system in Palmviken catchment, Arvika, is not up to the required standards.
- The system's response to a design storm in a coarse sewer model set-up (MOUSE) and a detailed coupled surface-sewer model set-up (TSR), respectively, are distinctly different in terms of outflow hydrographs and location of flooded manholes.
- System upgrade by a combination of subsurface and surface-oriented adaptation solutions, at a cost of 4.75 MSEK, can make the system meet today's standards.
- Short-term rainfall extremes are likely to increase until end of century, approximate uncertainty range 10–30 %.
- The total adaptation required to handle also the climate change impact costs 9.4 MSEK.

Concerning future rainfall, the climate change impact on short-term rainfall found in Arvika overall agrees with earlier estimates for Swedish conditions (e.g. Olsson et al. 2009), but the ensemble of six climate projections used here provides an increased confidence as compared with previous investigations. One limitation is that only one RCM (RCA3) was included in the ensemble; efforts to obtain short-term precipitation data from RCMs run at other institutes are ongoing. Another limitation already discussed is the scale mismatch between the RCM grid scale (50×50 km) and the very local scale relevant in urban hydrology. For improved impact assessment it is important to follow the development of RCMs towards higher spatial resolution. Evaluation of RCA3 precipitation at higher resolutions (25 km, 12.5 km, 6.25 km) is ongoing and will be reported elsewhere.

Concerning sewer system impacts, systems that already today has an insufficient capacity are not uncommon, in Sweden and elsewhere. Naturally, the additional costs for taking climate change into account in a system upgrade will be highly dependent on local conditions. A doubling compared with upgrading to today's standards is higher than in most other parts of Arvika, but may not be uncommon in a wider perspective. It should be remarked that the costs are calculated without consideration to related renovation and reconstruction in the catchment. In practice, storm water system upgrades are to the degree possible coordinated with e.g. replacement of pipes for sewage and/or drinking water, road maintenance and various land-use developments (parking lots, parks, etc.).

The results further highlight the impact of sewer model on the system response to a certain design rainfall. The MOUSE application is likely representative of the type of simulations commonly performed by engineering consultants when hired for evaluating system performance and designing upgrades. The TSR application represents a more ambitious and resource intensive approach, with a very detailed description of the urban environment and a surface-sewer coupling. That the results differ notably indicates that the results from a particular set-up and application are highly uncertain and that, when possible, different approaches should be used and evaluated. It may however be remarked that the suggested system upgrades were overall found appropriate in both models, even though their characterization of the performance of today's system were in some respects qualitatively different.

It may be concluded that future increased rainfall intensities caused by climate change may have a substantial impact on the performance of the storm water sewer system in Palmviken, Arvika. The magnitude of the expected increase is associated with large uncertainty, but all projections point in the same direction. In light of the expected lifetime of sewer system components, 50–100 years, the climate change impact should be considered when upgrading the systems but the added cost is significant. It must be emphasized that whether to take climate change into account or not may finally be a political decision. The many uncertainties (and controversies) surrounding the climate change issue makes it even further complicated, for engineers as well as politicians. Working in a team of experts on different models, of the climate as well as the sewer system, and to the degree possible quantify uncertainties involved, is desirable (if not necessary) to produce the proper results for supporting decisions in these matters.

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