Impacts for Climate Change in Urban Storm Runoff in Arvika, SWEDEN

Hideo Amaguchi[1], Akira Kawamura[1], Jonas Olsson[2] and Naoko Nakagawa[1]
[1]*Department of Civil and Environmental Engineering, Tokyo Metropolitan University, Minami-ohsawa, Hachioji, Tokyo, 192-0397, Japan*
[2]*Swedish Meteorological and Hydrological Institute, Norrköping, SE-601, Sweden*

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. Arnbjerg-Nielsen 2006; Bengtsson and Milotti 2008; De Toffol et al. 2009). In some cases trends are found but often not 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 if only 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 56 (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 74 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 are 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.

The city of Arvika in Sweden has experienced severe basement flooding problems in recent years, which are expected to further increase as a consequence of climate change and the associated increase in rainfall. In autumn 2000 Arvika was severely flooded because of prolonged raining within the catchment of the river Byälven during October and November. In summer 2006 a high-intensity storm event in Arvika caused street flooding and 30-40 basements were damaged.

The urban environment is characterized by its abundance of impervious surfaces (roofs, roads, parking lots etc.), from which runoff is rapidly generated as overland flow. Under normal conditions, this flow enters the sewage system to finally be drained to a receiving watercourse, typically a river or an open channel. If the generated runoff exceeds the storage capacity of the sewage system, surface flooding is caused by excess water outflowing from manholes and inlets. The flooding may be exacerbated by a simultaneous overflow of the receiving watercourse.

There is thus both a static and a dynamic aspect of the need for modeling of urban storm runoff and flooding. The static aspect represents the need to evaluate the properties and risks of flooding in a city in its present state, e.g. to produce flood risk maps as required by legislation. The dynamic aspect, on the other hand, reflects the fact that an urban environment as well as its climatological characteristics are constantly changing and the consequential need to evaluate flooding response to these changes.

In order to consider individual features in the urban environment, a few models have been developed from the view point of urban morphology. Rodriguez et al. (2003) proposed a non-grid-based GIS catchment description based on information in so-called urban databanks (Berthir et al., 1999), which consist of cadastral parcel, building, street, sewer system and river to calculate urban unit hydrographs. Rodriguez et al. (2008) employed a similar concept to develop an urban water budget model. Recently, vector-based basic GIS maps containing essentially the same information as urban databanks (except sewer system information) are becoming available also in major cities in Japan.

High-resolution spatial data such as that in urban databanks are potentially very useful for hydrological modeling, as a detailed and accurate representation of the catchment is at least as important in urban storm runoff simulations as the model equations and parameters. In order to take an advantage of such data, we have been developed a storm runoff simulation modeling including inundation events. In the urban modeling, a substantial amount of manual processing is required to make the available data suitable for hydrological model set-up, which includes dividing continuous stretches of roads and rivers into individual calculation elements and classifying in terms of hydrological properties such as perviousness or infiltration capacity. We have developed a methodology for performing this manual processing in a rational and consistent way (Amaguchi et al, 2006). By the approach, termed “urban landscape GIS delineation”, the flow paths in urban catchments can be represented with a very high level of detail. 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. The performance of urban storm runoff models depends on the model equations and parameters used the data used to describe the catchment as the model input is as well as important.

The urban landscape GIS delineation is a key component of a new framework for urban storm runoff and flood simulation: the Tokyo Storm Runoff (TSR) model. In the standard formulation of the TSR model all flow calculations are based on established hydrologic and hydraulic concepts and equations, but these can be easily 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. In this study, the TSR model is set up for an urban catchment of the Palmviken (Sweden) and applied to simulate the runoff response to 60 minutes storm with a return period of 10 years representing both today’s and future climate.

2 TOKYO STORM RUNOFF MODEL

2.1 Urban landscape GIS delineation

The definition of urban landscape GIS delineation is extraction and integration of fine-scale information about urban catchment including terrain, land use and drainage system used in high-density urban areas like central Tokyo. The delineation includes not only representation of individual geographical features but also specification of the hydrological connections between them. An urban catchment is in the model divided into two components: surface and subsurface. The surface component, which includes everything seen on a surface map, is in turn classified into block, road and river elements. The subsurface component comprises the sewer element. Individual elements are further divided into segments, which are the smallest spatial calculation units used in the TSR model.

Fig. 1 shows an example of a detailed map of an urban catchment obtained by urban landscape GIS delineation. An urban watershed is split into homogeneous elements such as roads, rivers and different land use components. Surface is classified into pervious area and impervious area. Rivers, roads, paved area and buildings are included in the impervious area. Pervious areas comprise grove, grass, playgrounds and others. In addition, urban landscape GIS delineation data also contains the sewer network system component that consists of pipe and manhole elements. For the runoff modeling, roads and rivers have to be divided into elements. Inside residential blocks, detailed land use information has to be added. This may include manual processing, in which map-based information is transferred to GIS format by appropriate GIS software.

2.2 Storm runoff process conceptualization

Fig. 2 shows a schematic of the rainfall-runoff process as represented in the TSR model. When rainfall begins, water falling on a land use element inside a block or a road forms pools, whereas water falling on a river adds to the river discharge. Rainfall excess from blocks flows out directly or indirectly through different types of surfaces and finally out into the nearest road. When a manhole exists inside the road, water flows through it to the rainwater sewer pipe conduit. When no manhole exists, water flows down the road to an adjacent road element. In a manhole, the water level is obtained considering the inflow from the road together with the upstream inflow from connected pipe conduits. In a pipe conduit, the water flow is obtained considering the water levels in the manholes located upstream and downstream, respectively. When the water level in a manhole exceeds ground level, water flows out and inundates the associated road. The inundated water either flows to adjacent road elements until a manhole that has not reached full inflow capacity is found. It may also flow into and flood a block, if the water level in the road is higher than that in the block (when the road water level decreases, water from the block flows back to the road). The water in the sewer pipe conduits eventually reaches the river channel, which finally drains in the catchment outlet. Infiltrated water from pervious land use elements inside blocks finally drains out into the river as long-term groundwater runoff, which is however at present not considered in the TSR model.

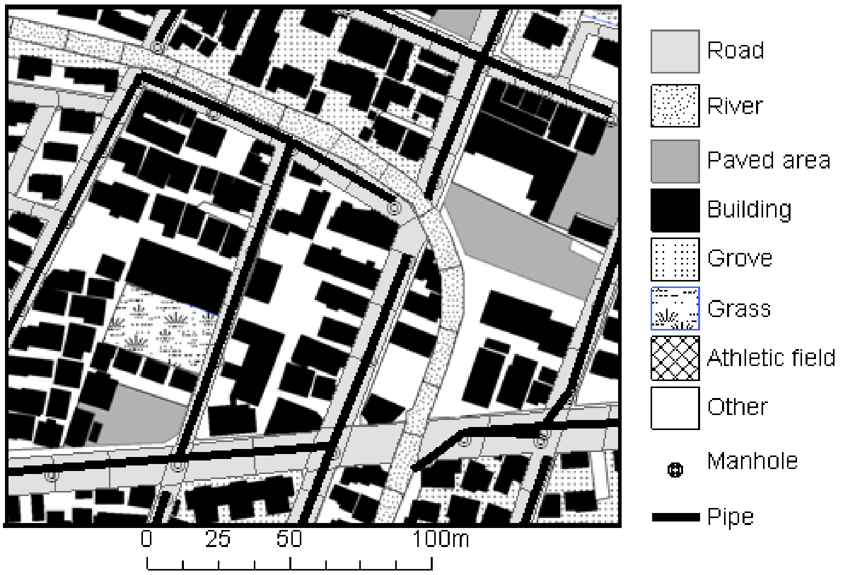

Figure 1. Map representing the different spatial elements considered in urban landscape GIS delineation.

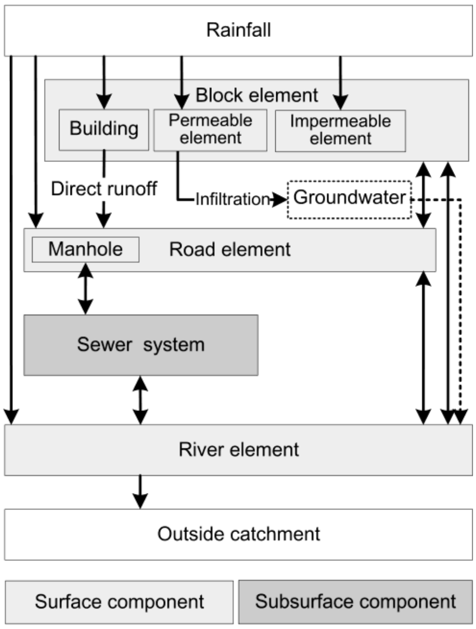

Figure 2. Schematic of the rainfall-runoff process of the TSR model.

3 MODEL APPLICATION TO THE PALMVIKEN CATCHMENT

3.1 Study Area

The study area selected for the model application is a small urban catchment, which is located in city of Arvika, Sweden, as shown in Fig. 3. Arvika is an urban area in Arvika Municipality in western Värmland County. Arvika's urban center lies on the north side of Kyrkviken, which is a distinct part of Lake Glafsfjorden. The study catchment will be termed “Palmviken catchment” and Fig. 3c shows this catchment in some detail. The Palmviken catchment area is ~0.92 km². It is essentially residential area with some minor parks, groves, fields, etc. Concerning the land use, ~47% of the surface is impervious.

3.2 Urban landscape GIS delineation and model set-up

Table 1 shows the data sources used in the urban landscape GIS delineation performed when setting up the TSR model for the Palmviken catchment. The road elements were divided into segments manually using GIS software. The ground level of road segments were calculated as averages obtained from a Geographical Surface Model produced by areal laser survey. The length of the road segments was manually adjusted to harmonize with the neighboring land use elements. The data source of main pipes and junctions were obtained from Arvika Municipality. In this study, more than 1 000 branches from main pipes to houses were added manually. Finally, all elements created were combined to completely specify the catchment. Fig 3 shows the final maps of surface component (a) and sewer element with road, block and river segments (b) in the entire study catchment. Table 2 shows the numbers and areas of the final GIS elements in the Palmviken catchment. It should be emphasized that more than 18 000 homogeneous elements (land use, road, river, manhole and pipe) were used to completely specify the small urban catchment.

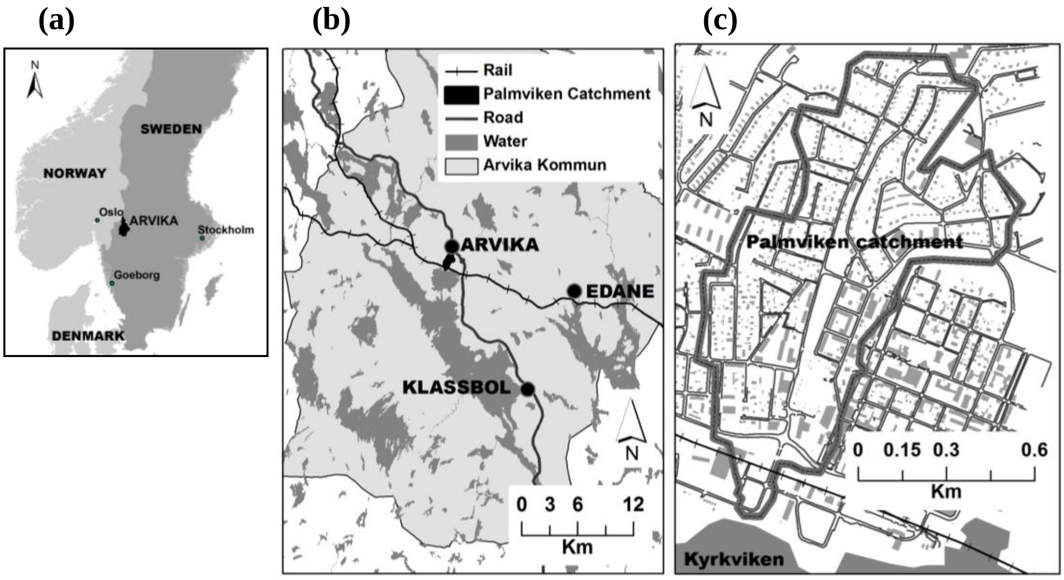

Figure 3. Location of the Palmviken catchment in Arvika Municipality, Sweden (a-b) and overview of the Palmviken catchment (c).

Table 1. Data sources required for urban landscape GIS delineation.

Data source (provider)	**Contents of the data**	**Data type**
Basic GIS delineation data (Arvika municipality)	Buildings and road	Digital
Air photograph (Arvika municiparity)	Land use information	Digital
Geographical Surface Model (Arvika municiparity)	Elevation of elements	Digital
Sewer pipe network map (Arvika municiparity)	Main sewer pipe network	Digital

Table 2. Numbers of feature elements and their total element area.

Element name		**Number**	**Total area** (m^2)
Road		4,663	167,372
Land use inside block	Impervious area	3,260	147,434
	Building	982	122,441
	Pervious area	9,176	483,582
	Total	18,081	920,829
Overland border		3,9226	-
Manhole		1,838	-
Pipe		1,838	-

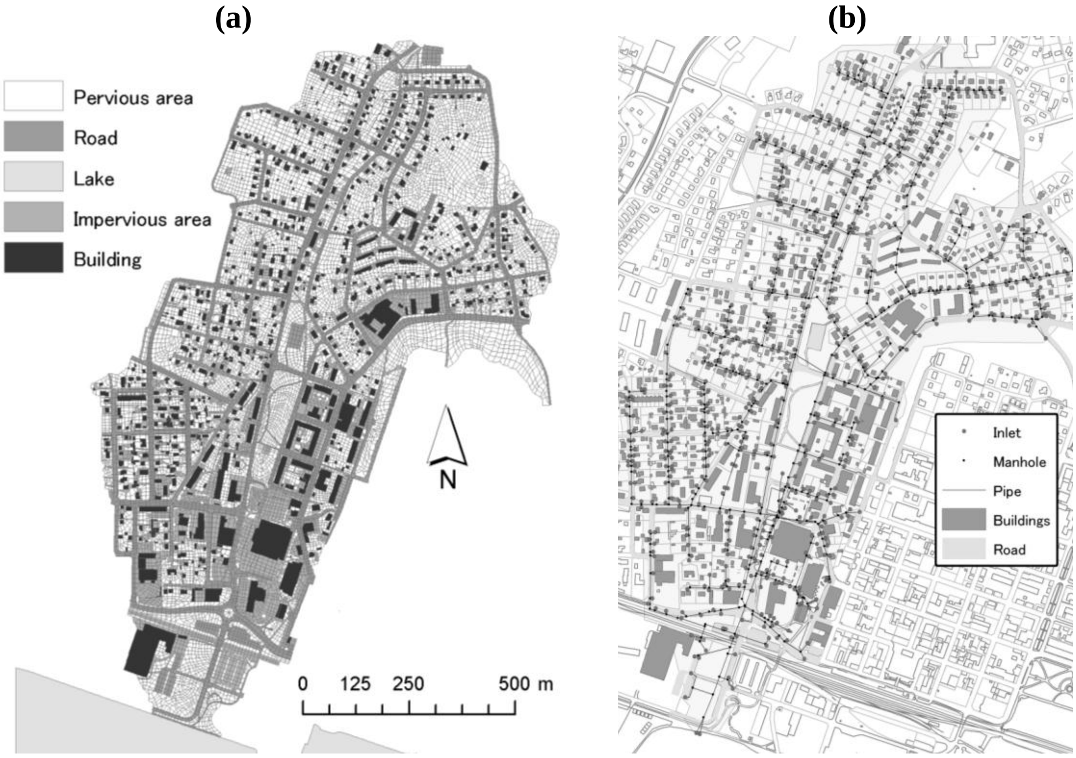

Figure 4. Final maps of overland component (a) and sewer element with road and buildings (b) in the Palmviken catchment.

(GCM) projections were dynamically downscaled over Europe to 50×50 km resolution by the Regional Climate Model (RCM) RCA3 (Kjellström et al. 2005). The 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.

From all projections, time series of 30-min precipitation intensities from a matrix of 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.

3.3 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 distributions were fitted to annual maxima for durations 30 min and 1 hr and the 10-year values calculated. The differences between periods REF and EoC were calculated and averaged over all grid boxes. The increase of the 10-year 1-hr rainfall intensity 200 from REF to EoC vary between approximately 10% and 35% in the projections (Fig. 3). The increase of the 30-min value is generally similar to the 1-hr increase. The most notable differences are 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. The other notable aspect in Fig 3 is the large increase of the 1-hr intensity in projection E4_A2, which is however known to generally predict an unusually large future precipitation increase.

Based on the results in Fig. 3, it was decided to use projection E5_A1B_3 in the sewer system simulations. Firstly, its results represent a most probable future increase, being close to the center of the range of variability in Fig. 3. Secondly, on a European scale, this member is generally found to reproduce historical climate more accurately than members 1 and 2. The sewer system model input was generated by 218 re-scaling the existing design storm using the results from projection E5_A1B_3 (Fig. 4). The rescaling was performed by first increasing the central 30-min period of the design storm, between minutes 00:10 and 00:40, with the 30-min increase found for E5_A1B_3. Then the remaining parts of the design storm were adjusted to make the total increase agree with the 1-hr increase for E5_A1B_3. It may be remarked that the EoC design storm is similar to today's 20-year storm.

3.4 Simulation of today’s and future design storms

The model was tested using a 60-mins storm with a return period of 10 years representing both today’s and future climate. The future design storms, representing the period 2071-2100 was estimated from analysis of extreme short-term rainfall as simulated by the global climate model ECHAM5 (Aghedo et al, 2010) and downscaled over Sweden by the regional model RCA3 (Kjellström et al., 2006; Olsson and Willen, 2010) under IPCC emissions scenario A1B. The peak rainfall intensity in the future design storm(denoted F3 below) is almost 30 % higher than that of today’s design storm(TC).

Table 3 shows the model parameters required. In this study, no attempt to calibrate or adjust parameter values is made but standard values are used. The initial loss parameters of impervious and pervious surfaces are obtained from Van de Ven (1992), who reviewed urban drainage model parameters. The values of final infiltration capacity are obtained from Ando et al. (1986), who developed a flood runoff model for urban basins using measured final infiltration capacities of different land uses. Roughness coefficients are not easily estimated from the urban landscape GIS delineation data. Further field investigation is needed to identify the relationship between surface roughness and flow in surface elements. Therefore, published values of Manning's roughness coefficient n are used here. The value of roughness coefficient used for building flow is 0.035 (Yen, 1991). The values of n used for surface flow shown in Table 3 are obtained from Inoue et al. (1998). The values were estimated based on model simulations of flooding in a similar type of urban catchment in Japan. The values of n used for sewer pipes and river channels are assigned as the standard roughness coefficient of concrete pipe (Mays, 2001).

In the simulations, the initial water levels at the sewer outlet to lake were set at 46.5 m. The initial water levels in the sewer system were approximated by the designed sewage flow conditions. Water levels in blocks and roads were set to zero as the simulation starts well before the start of the rainfall.

Table 3. List of required input data and parameters of the model.

Parameter	Value	
Initial loss L_i	Impermeable area	0.5
	Permeable area	1.0
Final infiltration capacity I_i	Grove	100.0
	Grass	20.0
	Athletic field	5.0
	Others	5.0
Building roughness coefficient n_b		0.030
		0.035
Surface roughness coefficient n	Between roads	0.043
	Other	0.067
Pipe roughness coefficient n		0.013

4 Results and discussion

Fig. 5 shows the simulated sewer discharge through outlet-pipe to Lake Kyrkviken. Although the 30 % increase in peak rainfall leads to only a 15% increase in peak discharge, the 23% increase in rainfall volume results in the 40 % increase in runoff volume.

Today’s design storm generates a number of flooded manholes in the current part of the catchment (Fig. 6a). Ideally, a storm water system should be able to handle a design storm without floods or other problems, but in practice this is often not the case. Even if the system could handle a 10-years storm when it was designed, the capacity may have been reduced with time because of e.g. damages to the pipes and/or an increased fraction of impervious surface as the city becomes density. In fact the catchment does experience floods in association with heavy storms, notably in July 2006 and August 2010, in line with the model results.

The future design storm generates more floods in the same area and also a bit upstream (Fig. 6b). Visually the difference is not very dramatic, but it is possible that the additional flooding has a substantial impact depending on the type of buildings and activities in the flooded area. Further evaluation will aim at investigating this issue in more detail.

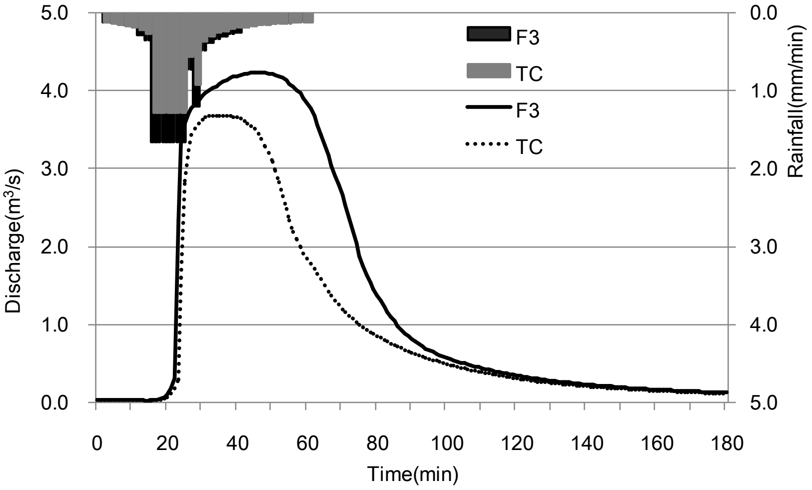

Figure 5. Flow through outlet-pipe to Lake Kyrkviken.

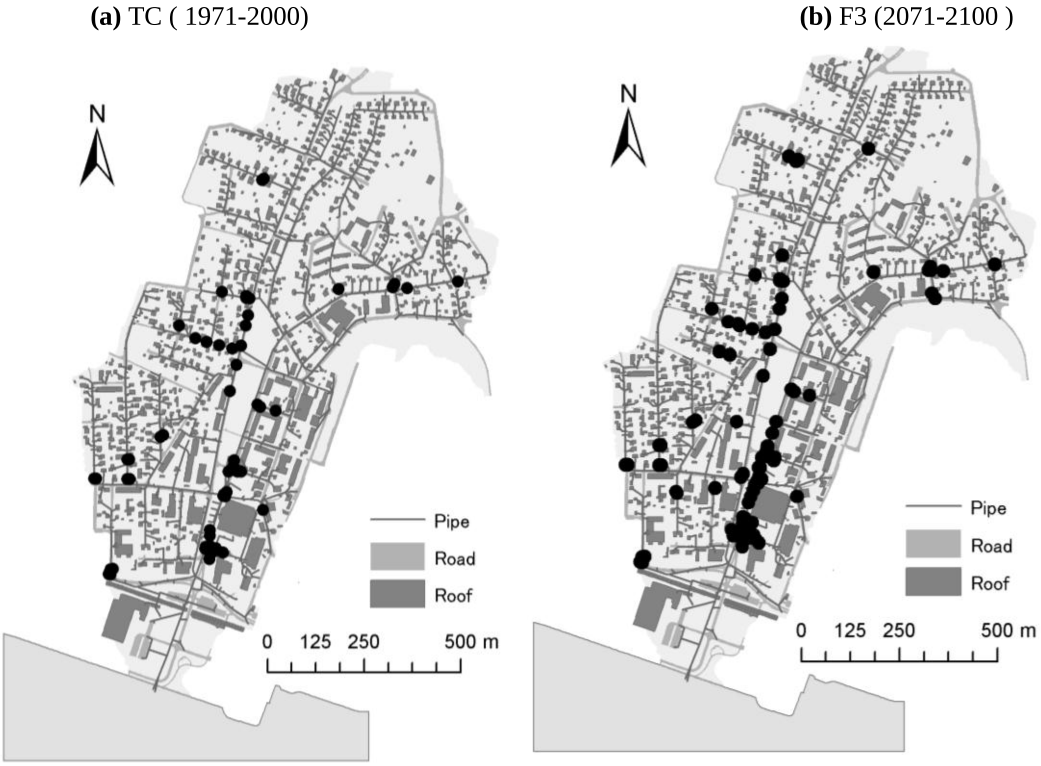

Figure 6. Flooded manholes for today’s design storm (a) and future design storm (b).

5 SUMMARY

In total, the results show that the TSR Model, based on a detailed reproduction of all relevant elements in an urban catchment, is able to simulate all aspects of urban flooding. Although in principle relatively straight-forward, this type of approach has until now not been practically attainable because of limitations in the resolution of available GIS data as well as limitations in computer power. We believe the methodology has a wide range of application for many practical problems such as evaluation of measures to improve flood protection facilities, which may include river channel improvements as well as installation of new runoff control facilities. Such proposed modifications may be easily implemented in the urban landscape GIS delineation and their function evaluated.

Another potential use of the model is detailed urban impact assessment of the higher rainfall extremes that are commonly expected in the future. The high level of detail used in the reproduction of the catchment is further very useful as it facilitates communication of the results, which is important in light of the recent trend towards increased stakeholder involvement in hydrological modeling. The conditions at specific critical locations can be easily extracted from the model output and used during discussions with the stakeholders involved.

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