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Climate Change and Urban Drainage

Future precipitation and hydraulic impact

Mats Olofsson

Luleå University of Technology
Department of Civil, Mining and Environmental Engineering
Division of Architecture and Infrastructure

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LULEÅ UNIVERSITY OF TECHNOLOGY

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Licentiate thesis

Division of Architecture and Infrastructure
Department of Civil and Environmental Engineering
Luleå University of Technology
SE-971 87 Luleå
Sweden

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Mats Olofsson
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Finally I would also like to express my gratitude to my family and all people around me that has helped and supported me in times of need. Without Kikki and our amazing dog Vassi to bring me joy and happiness it would not have been possible to make this thesis.

Thank you everyone!

Luleå, Mars 2007

Mats Olofsson

Abstract

Increasing global mean temperature influences the hydrologic cycle. In the 21st century, hydrologic change featuring more heavy precipitation events is very likely according to the UN Intergovernmental Panel on Climate Change, IPCC. This change will have a great impact on urban environments and infrastructures. In Sweden, precipitation during the winter will most likely increase by as much as 30 to 50 % by the end of the 21st century, while summer precipitation will decrease in the southern and middle parts of Sweden. Recent years have seen a number of floods caused by heavy rainfalls. With climate change, the problem with floods can be expected to continue and increase. To prevent adverse damage, modelling how the changes in precipitation and temperature will influence the urban drainage systems and how measures can be taken to prevent or reduce the consequences of floods has become increasingly important. The main objective with this thesis is to investigate the hydraulic impact in an urban drainage system due to the presumed increase in intense rainfalls.

Regional Climate models produce temperature and precipitation data for the future. The regional climate model RCA3 from Rossby Center at SMHI, produces data with a spatial resolution of 50*50 km and a temporal resolution of 30 min. To be able to use the climate data in urban drainage models, temporal and spatial resolution must be improved. A modification of the so-called Delta change method, where the changes are related to the rainfall intensity level, is presented to transfer the changes in rain characteristics from different future time periods to an observed series. For the study area, the climate model shows an increase of the highest intensities of up to 20 % for the 21st century. Effects of these changes are studied on an urban drainage system in the study area.

Results from the urban drainage simulations show that higher water flow-ratios in pipes, longer durations of floods, and more frequent floods can be expected if the climate continues to change with more high intensity rains, as the climate models predict. The maximum water levels in nodes were significantly higher for all future time periods that were simulated. Even in the near future (2011-2040), maximum water levels in nodes were >0,1 m higher compared to today's climate. Since the renewal rate of pipes in the existing urban drainage system is relatively slow, emphasis must not lie only on city development but also on future climate change. Design criteria, therefore, need to be changed according to changes in precipitation. Weak spots in the system must be identified for the adaptation to be as effective as possible. Knowing when, where, and how to put the correct measures when adapting the urban drainage system is essential for efficient management.

Climate change also affects urban drainage in different ways, depending on where in Sweden the city lies. In northern Sweden, problems can arise with changing snowmelt patterns, for example. Further research involves an analysis of the consequences that higher water levels, increased max flow, and higher seasonal variations will have and of the adaptation strategies required not only for the urban drainage systems but also for other infrastructures.

Sammanfattning

En ökad global medeltemperatur påverkar den hydrologiska cykeln och enligt FNs klimatpanel, IPCC, är det väldigt troligt att detta leder till fler häftiga regn under 2000-talet. Förändringen i nederbörd får stor inverkan på den urbana miljön och infrastrukturen. I Sverige ökar nederbörden vintertid med så mycket som 30-50 % i slutet av 2000-talet medan sommarnederbörden minskar i mitten och södra delarna av Sverige. De senaste åren har uppvisat ett antal översvämningar orsakade av häftiga regn. Med klimatförändringen kommer troligtvis problemen med översvämningar fortsätta att öka. Därmed har det blivit ännu viktigare att modellera hur förändringar i nederbörden påverkar det urbana dagvattensystemen och vilka åtgärder som kan sättas in för att förhindra allvarliga översvämningar och skador i framtiden. Huvudsyftet med den här avhandlingen är att undersöka vilken hydraulisk effekt den förändrade nederbörden har på urbana dagvattensystem.

Regionala klimatmodeller simulerar bland annat framtida temperatur och nederbördsdata. Den regionala klimatmodellen RCA3 från Rossby Centre på SMHI, producerar data med en spatial upplösning av 50*50 km och en tidsupplösning av 30 min. För att kunna använda klimatdata i en urban dagvattenmodell måste den spatiala och tidsmässiga upplösningen förbättras. En modifiering av den så kallade Delta Change-metoden, där förändringarna är relaterade till intensiteten i nederbörden presenteras för att överföra förändringar i framtida regnkarakteristika till en uppmätt regntidsserie. För försöksplatsen visar klimatmodellen en ökning av de högsta intensiteterna med upp till 20 % under 2000-talet. Vilka hydrauliska effekter denna förändring ger upphov till studeras i en modell av ett urbant dagvattensystem från en försöksplats i södra Sverige.

Resultaten från simuleringarna visar att större vattenflöde i ledningarna, längre varaktighet vid översvämningar och mer frekventa översvämningar kan förväntas om klimatet fortsätter att förändras i linje med vad klimatmodellerna förutspår. Vattennivåerna i brunnarna var signifikant högre för alla tidsperioder som simulerades. Även i den närmsta perioden (2011-2040) blir den maximala vattennivån i brunnarna 0,1 m högre jämfört med dagens klimat. Eftersom förnyelsetakten för ledningsnäten är relativt långsam så bör man inte bara titta på stads- och befolkningsutvecklingen utan även förändringar i klimatet när åtgärder planeras. Att veta när, var och hur åtgärder ska sättas in för att anpassa systemet är viktigt för en effektiv förvaltning av ledningsnäten. Svaga länkar i systemen måste identifieras för att anpassningen ska bli så effektiv som möjligt. Dimensioneringskriterier behöver ändras i linje med förändringar i nederbörden.

Klimatförändringen påverkar också den urbana dräneringen på olika sätt beroende var i Sverige som staden ligger. I norra Sverige kan exempelvis problem uppkomma med förändrade mönster för snöbildning och snösmältning. Mer forskning behövs för att analysera vilka konsekvenser högre vattennivåer, högre flöden och större säsongsvariation får samt vilka anpassningsstrategier som behövs inte bara för det urbana dagvattensystemet utan även för övrig infrastruktur.

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List of publications

Paper I: Olsson J, Olofsson M, Berggren K, Viklander M, (2006), Adaptation of RCA3 Climate Model data for the specific needs of urban hydrology simulations, Proceedings of the 7th International Workshop on Precipitation in Urban Areas, St. Moritz, Switzerland, 7-10 December 2006, Accepted for submission of full paper for a special issue of *Atmospheric research*

Paper II: Berggren K, Olofsson M, Viklander M, Svensson G, (2007), Tools for measuring Climate Change Impacts on Urban Drainage Systems, Accepted for publication in *Proceedings of the 6th international conference on sustainable techniques and strategies in urban water management* Lyon, France, 25-28 June 2007

Paper III: Olofsson M., Berggren K., Viklander M, Svensson G, (2007), Hydraulic impact on urban drainage systems due to climate change, Submitted to *Journal of Hydrology*

In addition, the following paper has also been published. It is, however, not included in this licentiate thesis.

Olofsson M, Östman A, (2006), Optimizing Dynamic Network Configurations, *Proceedings of the 9th AGILE Conference on Geographic Information Science*, Visegrád, Hungary, 2006

1 Introduction

Climate change and its effects is and will probably continue to be one of the most important problems the world needs to deal with throughout this century. Rapid changes have occurred during the last years; for instance, the carbon dioxide radiative forcing increased between 1995 and 2005 by 20 % and the last twelve years (1995-2006) have contained eleven of the warmest years since measurements started in 1850 (IPCC, 2007). Increasing global mean temperature influences the hydrologic cycle. In the 21st century, hydrologic change, with more heavy precipitation events, is defined as being very likely by the UN Intergovernmental Panel on Climate Change, IPCC (2007). This change will have a great impact on urban environments and infrastructures. In Sweden, precipitation during the winter will most likely increase by as much as 30 to 50 % by the end of the 21st century, while summer precipitation will decrease in the southern and middle parts of Sweden (Bernes, 2003).

Recent years have seen a number of floods in urban areas around the world caused by heavy rains. Because these intense rains are likely to occur more often in the future, further damage to people and real estate can be expected. To prevent adverse damage, modelling how the change in precipitation and temperature will influence the urban drainage systems and how measures can be taken to prevent or reduce the consequences of floods has become increasingly important. This thesis presents methods and results on how to simulate what effect the changed precipitation will have on urban drainage.

1.1 Climate models

Climate models are complex data models simulating the earth's behaviour with mathematical descriptions of the climate system and interaction between components. Various emission scenarios with different assumptions, e.g. population, energy demand, and land use, are used to give input to the climate model (Berns, 2003). The essential input to the climate model is the level of emissions of radiatively important gases. IPCC has defined about 40 scenarios that can be divided into scenario families (see Figure 1) in its Special Report on Emission Scenarios, SRES (Nakicenovic et al., 2000).

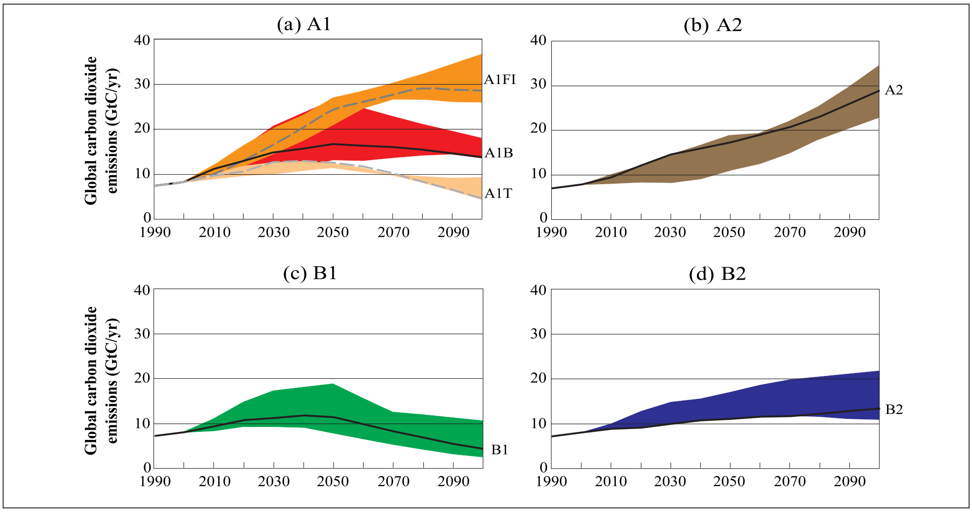

Figure 1. CO_2 emissions in total annual gigatonnes of carbon from all sources 1990 – 2100 for the scenario families (A1, A2, B1, B2). A1 has three groups with fossil-intensive A1FI, non-fossil intensive A1T, and the balanced A1B. The colored emission bands show the range of the 40 harmonized and non-harmonized scenarios. Each group has an illustrative scenario in solid line (dashed for A1FI, A1T). (Nakicenovic et al., 2000)

Regional climate models built on data from the global models give a more detailed output covering a specific area. In Sweden, a regional model covering Europe is developed at the Rossby Centre, which is part of the Swedish Meteorological and Hydrological Institute, SMHI. The latest regional atmospheric climate model is called RCA3 (Kjellström et al., 2005) and uses output from the global European Centre Hamburg Model Version 4, ECHAM4 (Roeckner et al., 1996). RCA3 generates an output with a 50*50 km spatial resolution and a temporal resolution of 30 minutes (min) for the 140-year simulation period (1961 to 2100). The temporal resolution is better than most previous climate models, which makes it better suited for the extraction of short-term rainfall properties than previous models.

1.2 Urban drainage models

Urban drainage systems are mainly either separated (storm water and waste water in separate pipes) or combined. In many cities, sewerage systems are partly combined, especially in old parts of the cities (e.g. Butler and Davies, 2004). Computer-based urban drainage models were first seen in the late 1970s. The deterministic models cover hydrological and hydraulic aspects from, for example, the input of precipitation for each catchment to the hydraulic effect on the network with flow-rate and water levels (Butler and Davies, 2004). Two of the most commonly used models are SWMM (Storm Water Management Model), which is developed by the US Environmental Protection Agency and MOUSE (Modelling of Urban Sewers), developed by Danish Hydraulic Institute

(DHI). This study uses Mike Urban (DHI, 2005), which is based on MOUSE and ESRIs ArcGIS platform.

1.3 Linking urban drainage and infrastructure

Floods from heavy rains and increasing sea level can lead to immense costs as reported in the Stern Review (2006), in Europe the floods in 2002 lead to at least 15 bn Euro in economic losses (EM-DAT, 2007). Floods caused by insufficient capacity in urban drainage systems can cause great damage to other infrastructures as well. In Sweden an average of about 600 basement floods occurred each year 2003-2005 (Svenskt Vatten, 2007). Both the separated and the combined systems will be affected by increased heavy rainfall and the effect will probably be worse in combined systems where, for example, increased basement flooding can be expected. There are different approaches to assessing impacts in urban drainage systems due to a changed climate, but a frequently used way is to perform model simulations of urban drainage systems (e.g. Ashley et al., 2005; Semadeni-Davies et. al.2006; Waters et al., 2003; Niemczynowicz, 1989, Evans et al, 2004a,b). To support policy and decision making on how to manage urban drainage systems in a time of climate change, analysis for adapting existing systems together with other infrastructures is needed.

1.4 Precipitation adaptations

An important problem with climate data as input to urban drainage models is the translation of climate model precipitation for urban usage. The precipitation data is valid for a spatial resolution of 50*50 km, whereas the urban rainfall applies to point rainfall. The temporal resolution is also of great importance since urban drainage models often have short concentration times. Yet another problem is the limitations of the climate model's description of high-intensity rainfall. Intensities and patterns of heavy rainfall are not very well reproduced since they are greatly affected by the local scale (IPCC, 2001). Adaptation of precipitation data for use in urban drainage models is, therefore, essential to finding relevant effects of the changed climate. Advanced transformation and dissagregation (e.g. Koutsoyiannis et. al., 2003) are required if the precipitation data is to be a direct input in the data model. Another common approach is to apply a "climate factor" to the design rainfall or an observed rainfall series to simulate an increase in rain intensity. This factor is calculated from the climate model data in different ways. Quantification of future high-intensity rains in Denmark has been studied by e.g. Arnbjerg-Nielsen and Onof (2006), Jørgensen et al. (2006) and Grum et al (2005). In this thesis, a future relative change in precipitation is transferred to an observed rainfall time series via a Delta change method.

2 Objectives

The main objective is to study the effects of climate change on urban drainage, especially the effects caused by a presumed increase in intense rainfalls in Sweden. The objective is also to find methods to adapt or transfer climate model precipitation data for use in urban drainage computer simulations. Furthermore, the objectives have been to investigate which possible impacts the changed precipitation will have regarding hydraulics in an urban drainage system and what effects these will have on infrastructure.

3 Method

To assess impacts on urban drainage systems a strategy has been developed, Figure 2. The boxes in bold lines are considered in this thesis: the transfer of climate rainfall data to an observed rainfall series via a Delta change method and to use this data in urban drainage simulations to study the hydraulic impacts on an existing urban drainage system.

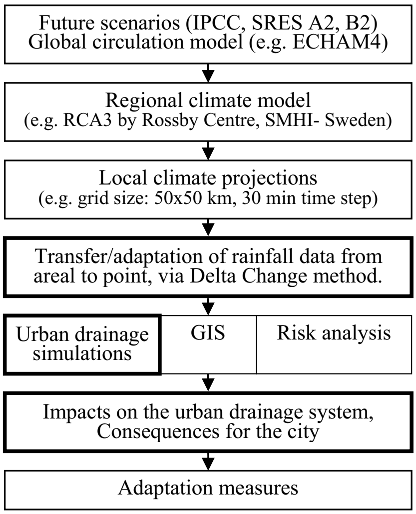

Figure 2. Main strategy for assessing impacts on urban drainage systems

3.1 Study area

The area of study is a suburb to a small city in the south of Sweden. The area has a population of 3 000 and a contributing catchment area of 54 ha, of which 20 ha is impervious. The urban drainage system is separated, thus it contains only storm water. The system contains 410 nodes and is designed according to the current design standards (Svenskt Vatten, 2004), which means that the system should manage at least rains of a 10 year return period without surface flooding. This area was selected as a suitable study area because a calibrated MOUSE-model from the urban area was available.

3.2 Precipitation data

Output from the Rossby Centre RCA3 climate model covering the study area was extracted and analysed. This study uses climate model data derived from IPCC SRES scenario A2 and B2, which are intermediate. The climate precipitation data was compared with a 14-year time series of observed tipping bucket rainfall data from the study area (Hernebring, 2006). RCA3 generates an accumulated precipitation volume of about 70 % more than the observed series for the period 1992-2000. Percentage of dry periods for the observed series is 96 %, while climate data show dry periods of about 51 %. Both the high accumulated value and low percentage of dry periods can be explained by the climate model overestimating small intensities. Of course, a lower percentage is expected since it represents a spatial average. But when compared to similar spatial observations, the climate model still overestimates the frequency of low intensities. The main interest, however, lies in the maximum intensities where climate model data shows a maximum of 3.3 mm while observation shows 15mm. To compare intensities between areal and point measurements, areal reduction factors (ARF) can be used. For a duration of 30 min and an area of 3000 km2 ,the factor that specifies how much a point value is reduced is 0,41 (NERC, 1975). Thus, 15 mm will be reduced to about 6 mm when considering the spatial resolution. This is still more than the climate data but the 15 mm value is somewhat extreme and the next highest intensities in the observed data are lower. But it is probably also the limitations in the rainfall generation in the climate model that affect the outcome of the highest intensities. Overall, the climate model appears to reproduce rainfall covering the study area reasonably well.

To emphasis the need for high-resolution temporal and spatial data in urban drainage modelling, a comparison was made between tipping bucket data, climate data, and aggregated tipping bucket data aggregated to 30 min to fit the temporal resolution of the climate model data. Three different comparisons with spatial and temporal resolution visualized in Figure 3 were made.

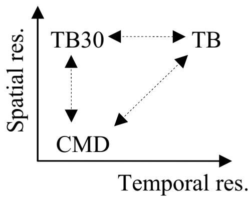

Figure 3. Comparison between TB: Tipping bucket, TB30: Tipping bucket, and CMD: Climate model data 30 min

Transferring change in rain characteristics from climate precipitation models to urban drainage models is essential to find out how the precipitation change will affect the urban drainage system. Delta change is a method to scale the observed rainfall series by a percentage increase or decrease based on the differences in future climate model data compared to today's climate model data. Different delta factors can be applied, for example for high and low intensities (e.g. Semadeni-Davies et al., 2006). Since DC-factors are applied on observed point source data, the assumption is that a comparison between low- (temporal and spatial) resolution and high-resolution data must be made. This is not without complication but is necessary because of the limitations in resolution and rainfall- generating mechanisms of current climate model data.

A modification of the so-called Delta change method with calculated relative changes is proposed to transfer the change in precipitation to an observed gauge data series. The delta factors vary continuously according to intensity level. The 140-year period of climate data was divided into four 30-year sub-periods to represent different climate perspectives: today's climate (TC), 1971-2000; near future climate (FC1), 2011-2040;

intermediate future climate (FC2), 2041-2070; and distant future climate (FC3), 2071-2100. The climate periods correspond to other investigations on climate change made at SMHI.

3.3 Data model and parameters

The urban drainage data model covering the study area is a separated system. It was modified from the original system but was used as an example of a common storm water system. Since the focus is on comparing impacts from different time periods, the starting condition is not important. To decrease the massive information from 10 years of simulation in each time period, 120 nodes from the system were selected as representatives of the system. The selection of nodes was made from the following criteria: (1) nodes representing swales were removed from the result file, (2) nodes with depth less than 1,0 m were removed from the result file, and (3) if several nodes were close to each other, only a few of them were kept. The system has three outlets, two shown in Figure 7 in the upper part and one in the lower east part.

Parameters that were chosen to describe the impacts are as follows:

- Maximum levels in nodes: an indicator of system capacity, which, in a simple way, describes differences between the time periods.
- Exceeded levels: exceeding of the ground level or a critical level 0,5m from ground. This is described by
  - Number of nodes affected: describes from which nodes (and parts of the city) water is exceeding the ground or critical levels, thus indicating the capacity of the system.
  - Frequency: describes how often the levels in the nodes are exceeded and describes which nodes (and parts of the city) are more often affected by water exceeding ground (or critical) levels.
  - Duration: describes how long water is exceeding the ground (or critical) level, indicating the possibility of damage due to flooding.
- Pipe flow-ratio (Q/Q_{full}): describes how the maximum flow-ratio in the pipes will change.

Statistical comparison is made for maximum levels to see if there are significant differences between the time periods. Matched pairs are used due to the lack of homogeneity between nodes (Montgomery, 2001).

4 Results

4.1 Temporal and spatial resolution in precipitation data

From the maximum water levels in nodes compared within matched pairs parameter, the statistical analysis verifies that the temporal resolution has a great impact on the results. A T-test shows that, at a 95 % confidence level, the tipping bucket rainfall data results in a 0,25-0,42 m higher maximum water level compared to the 30-min aggregated series. When the impacts from spatial resolution are compared, the levels are between 0,17 – 0,35 m higher for aggregated tipping bucket data than climate model data. The comparison with both spatial and temporal difference shows 0,35 – 0,44 m higher levels for tipping bucket than climate model data. The need for adaptation of climate model data to suit urban drainage modelling is evident.

4.2 Adaptation of climate precipitation data

An intensity distribution of the climate model rains for the summer period in today's climate (TC) and future time periods (FC1, FC2, FC3) shows that the highest intensities will increase in the future, e.g. ca: 10 % of the rains in FC3 have higher intensities than the corresponding rains in TC (for A2). The distribution is calculated by averaging the first, second, and third 10-year period for each 30-min rain within each 30-year period, respectively. From the intensity distribution, delta factors were calculated by taking the ratio of the future time period with TC for each percentile. When comparing delta factors for the different time periods, it is clear that summer precipitation will decrease for all intensities but the highest. FC3 in A2, in particular, shows a distinctive decrease in summer precipitation for the lower intensities and a clearly visible increase in the highest intensities. Third-order polynomials can be used to smooth out fluctuations in the delta factors; however, these can affect the highest intensities to become lower. B2 shows somewhat similar delta factors, but B2 FC2 has generally higher factors than A2 FC2.

The factors applied to a tipping bucket series aggregated to 30 min are shown in Figure 4. High intensities will have a greater increase. In practice, all tipping bucket registrations within a 30-min period were applied with the same factor.

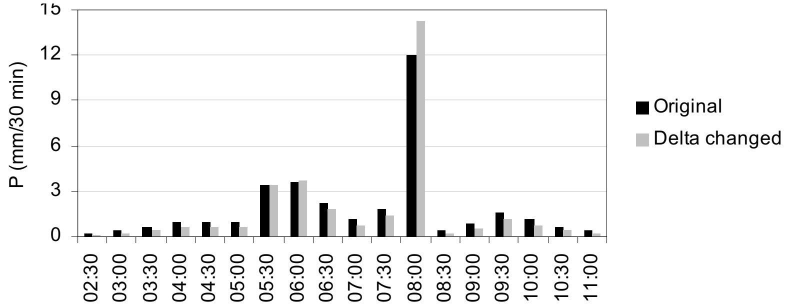

Figure 4. A sequence of 30-min rainfall intensities, observed (black) and modified by Delta change for FC3, A2 (grey).

The change in characteristics for each time period can be evaluated by calculating the return periods for the whole tipping bucket series. The return period for 1 year and above is shown in Figure 5. Higher intensity rains (with higher return periods) will increase more than lower intensity rains. The highest return period will more than double for time period FC3. This is the natural consequence of applying higher delta factors for more intense rains. If other methods had been used to transfer the change in precipitation from climate model data to a measured data series, the change in return periods would have looked more uniform, regardless of the return period.

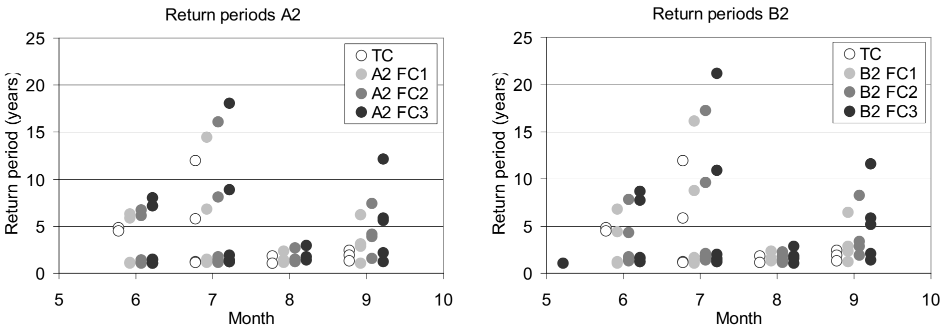

Figure 5. Return periods calculated for a design storm with a maximum average intensity for the duration 10 minutes (C. Hernebring, personal communication, 2007-03-06). Values for the observed rainfall series (TC) and when Delta change factors have been applied to the future time series (FC1,FC2,FC3) for scenario A2 (left) and B2 (right). Rains with a return period of 1 year and above based on Dahlström (1979), Z-value=12.

4.3 Urban drainage simulation

4.3.1 Maximum water levels in nodes

At a confidence level of 95 %, the maximum water levels in the nodes were higher for all the future periods (FC1, FC2, FC3) compared to today's (TC) levels, for both scenarios A2 and B2. The difference in maximum water levels in nodes for FC1 compared to TC is between 0,10-0,16 m (A2) or 0,12-0,18 m (B2). Confidence intervals for the differences are presented in Figure 6. The width of the confidence intervals for both A2 and B2 is about 0,05 m for near future time periods (FC1-TC), increasing up to ca 0,12 m for distant future time periods (FC3-TC).

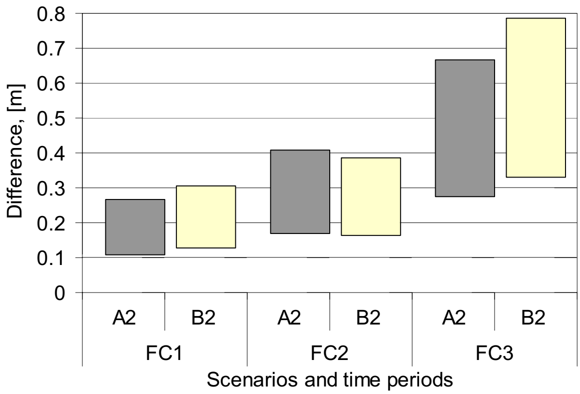

Figure 6. Difference in maximum water levels in nodes, 95 % confidence interval for mean difference between TC and future time periods (FC1, FC2, FC3).

There is also a significant statistical difference between A2 and B2, for the time period FC3, at 95 % confidence level. A2 and B2 FC1 show a small difference while FC2 does not.

4.3.2 Pipes and nodes affected by flow and exceeding of water levels

Flooded nodes, critical levels reached, and pipe flow-ratio in the network are shown in Figure 7. For TC, floods are mainly occurring in two places while, in FC3, floods have spread over a wider area and to other locations as well. The three circles show regions that are most affected by the changed precipitation and indicate where measures need to be taken. Maximum storm water flow ratio (Q/Qf , flow-rate / flow-rate full) in the network has increased considerably between the two time periods. Values for A2 FC3 are similar.

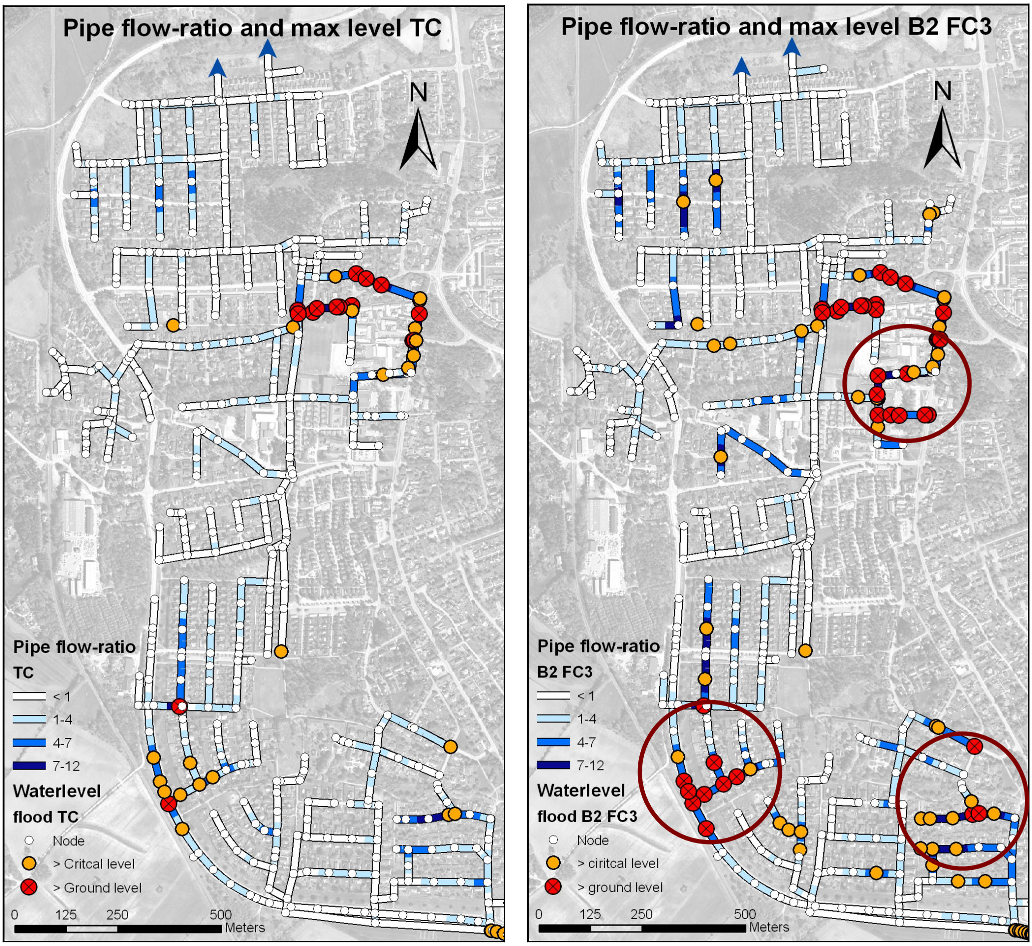

Figure 7. Left: Flooded nodes and nodes where critical level is reached for TC and in the complete system. Network shows water flow-ratio (Q/Q_f). Right: Flooded pipes and nodes, scenario B2, in future time period FC3. Network shows water flow-ratio (Q/Q_f).

4.3.3 Frequency

Figure 8 shows an increase in affected nodes in all intervals and especially in nodes where the frequency of flood is one or two. Since the numbers of events are limited, only three intervals are given. The tendency is that future precipitation will increase the number of flooded nodes and also the frequency of the floods. Higher frequencies of floods can be seen, even in the near future time period; consequently, areas that have experienced floods can expect more frequent floods in near future.

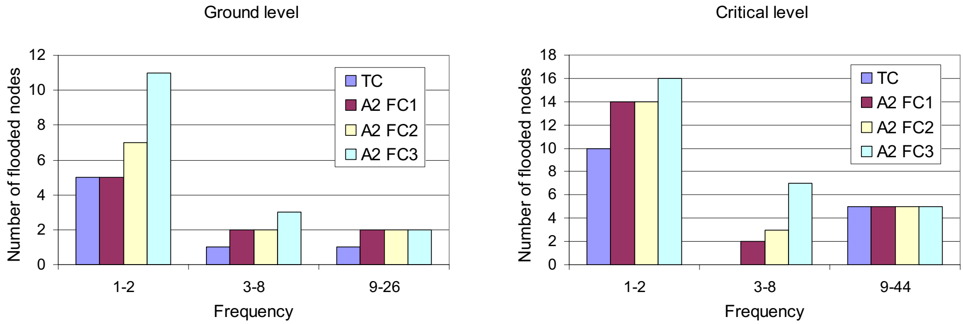

Figure 8. Left: Frequency of flooded nodes divided into three intervals for A2. Right: Affected nodes for critical level in A2. Values for B2 are similar.

4.3.4 Duration

The number of unique flood events and floods with long durations increases for all future time periods and scenarios. Each node may be flooded several times during the period. Maximum duration in nodes that are flooded shows an increase for each time period in A2. Since only a limited number of nodes are flooded in each time period, results should be carefully interpreted. Most nodes show a doubled duration in A2 from TC to FC3; for example, the highest duration for TC is 41 min and the corresponding durations are 63 min for FC1, 69 min for FC2, and 85 min for FC3. Durations in B2 for FC1 and FC2 have more even values than A2. The maximum duration difference in A2 was from TC 10 min to FC3 108 min and, in B2, from TC 27 min to FC3 101 min.

5 Discussion

5.1 Climate model precipitation

From the climate precipitation data analysed, one property that differs from measured data is the dry and wet periods. Wet periods seem to be overestimated in the model. To decrease the difference, a threshold value can be applied to the model data. However, the low intensities do not affect flooding caused by summer rains but can affect the snow build up and snowmelt pattern. When Delta change is used, the temporal structure of the rainfall in future periods is presumed to be the same. This is both an upside and a downside of the Delta change method. For spring, summer, and early autumn rain, it is probably a realistic presumption but might not be good for winter precipitation. In northern Sweden, changing snow accumulations and snowmelt will affect the runoff more than in southern Sweden. In order to better assess snow build up, it could be more effective to run the climate model data directly (with an applied threshold value), or be very careful and apply the Delta change factors in a way that the total rain amount will reflect the increase in winter precipitation. The long-term change in water volumes, for example, can also probably be analysed by using the model data directly, but, for the intense rains, better temporal and spatial resolution is needed. Either way, the characteristics of the climate data must be analysed when choosing a method.

A way to deal with uncertainty in climate models is to use scenarios that will give an interval of future change. But, even then, the results must be interpreted with great caution since climate models are very uncertain for intense rains; better representation of intense convective rains will help the accuracy of urban simulation. Hopefully, future climate models will also produce rainfall with better spatial and temporal resolution that can be used directly, or with minor adaptation, in urban drainage models.

Apart from the mismatch in temporal and spatial scales, all climate change impact studies raise the question on how accurate the climate models and future scenarios are. Comparable results might be obtained with other methods like a simple multiplicative factor or more advanced (e.g. statistical) methods. These methods also have disadvantages and uncertainties. The employed Delta change seems to be a straightforward way to more precisely transfer the future change in intense rains.

Climate models and knowledge about of how the earth's atmosphere works are continuously being improved, which will lead to better estimations in the future. Therefore, always having up-to-date data from the climate models is important. More parameters are also needed in the impact analysis. Temperature is one important parameter that needs to be addressed when analysing cities in mid and northern Sweden. For instance, the climate model shows that more precipitation in the wintertime will also be followed by variations in the temperature and, hence, will cause problems. Soil moisture is another parameter from climate models that affects the runoff volumes.

5.2 Hydraulic impacts

The parameters used in this study have a fast hydraulic response and reflect the effects of intense rains. Most of these parameters have been used in literature, e.g. peak discharge/flows (Waters et al, 2003), and number of properties flooded (Ashley et al, 2005). Other parameters, e.g. runoff volume (Waters et al, 2003), time to peak discharge (Waters et al, 2003), inflow to WWTP (Semadeni-Davies, 2004), and combined sewer overflow (Niemczynowicz, 1989; Semadeni-Davies et al, 2006) are, however, not used in this thesis.

The results from the simulation show that if the climate model is correct, increasing flooding will be a problem in the future. Even in the near future, the increase in maximum water levels (>0,1 m) is statistically significant. With higher water levels and higher water pressure, risk is evident for leakage from pipes, which can cause erosion of fill materials, for example, which, in turn, can cause damage to infrastructures and real estate.

Not surprisingly, all results from the urban drainage simulation illustrate more flooding with more intense precipitation events in the future. But more investigation is needed in order to assess where, what, and when action must be taken. The needs differ with every urban drainage system and so does the effect of the climate change. In places with more intense summer rains, an increase of capacity, overflow, or storing possibilities is needed, while the change in winter precipitation and temperature may increase the need for other measures.

The exceeding of ground levels and critical levels in the system gives an indication of where the hydraulic capacity is limited. In addition risk and economical effects can be calculated from more parameters. When weak spots in the urban drainage system have been identified, it is important to follow up and investigate where measures have had the most effect. A wider picture is needed to be able to develop adaptation strategies for the specific system.

5.3 Linking urban drainage and infrastructure

To be able to evaluate further effects on the city, a wider analysis is needed. Risk assessment through a Geographic Information System (GIS) is a way to get an overview of future climate change impacts on urban flooding. Water level output from the urban drainage model can be inserted in a GIS to show spreading and consequences of flooding. To be able to do correct modelling, having an accurate GIS-model is important. The digital terrain model is especially important for calculating surface water paths and for calculating where flooding will have consequences. To create an accurate model, high-resolution elevation data is needed. As shown by Balmforth and Dibben (2005), laser scanning is an excellent tool to get elevation data for urban drainage modelling with accuracy of up to +/- 150mm. This method is, however, expensive so, for most areas, other methods or existing data are better choices, from an economic perspective.

Extensive analysis can be made with data covering for example infrastructure, real estate, roads, demographics, soil layers, future city plans, repair costs for different damages and different areas. Social aspects and political economy may also play a vital role. A vulnerability layer combining these factors or several vulnerability layers with different aspects can be combined to find places that are important to protect and where measures need to be taken. Through a GIS analysis, each aspect can be walked through and analysed.

With asset management, the risk and cost of a damaged basement or flooded road, for example, can be calculated and the cost of a flood can be compared to what it would cost to act with preventive measures. This way, the correct measures are easier to identify and validate. A 3D-model can tell when problems will arise in all levels: when basements will flood and when roads need to be closed due to land slide risks, for example. The next step could be to enter more dynamic data, such as for traffic.

One way to deal with different vulnerabilities in different parts of the city can be to divide the city into vulnerability areas. Different aspects and parameters are analysed and, apart from information such as infrastructure, soil, land usage, topography, drinking water network, and demography, the sewage network and its connection to the infrastructure need to be taken into account. The result from the analysis is then combined with a security criterion for the urban drainage system. If the area is sensitive and, hence, has a high vulnerability, the urban drainage network within that area needs to be extra safe. For instance, the network in the vicinity of a hospital needs to handle a 100-year rain event, while the network in a recreation area only needs to handle a 10-year rain event. The problem with this solution is, of course, that flooding in one area can lead to flooding in another area. This problem could be dealt with in different ways, for instance building detention basins or building rerouting possibilities to areas that are less sensitive.

6 Conclusions

Even though summer precipitation decreases in the study area, the climate model shows that precipitation intensity will increase, hence more flooding can be expected. If the climate models are correct the maximum water levels in the urban drainage system will increase, hence more and longer lasting floods will occur. The frequency of floods will also increase. Effects that are not seen on ground level, such as higher flow-rate in the pipes, can lead to other problems, such as pipe leakage and its consequences.

A modified Delta change method was constructed to transfer the rain characteristics of the climate model data to an observed rainfall series. It appears suitable to transfer the trend with increased maximum intensities because it gives more detailed results than the standard Delta change method with a fixed increase of all intensities. The results from this paper point out the necessity of climate model rainfall data dissagregation or transformation in both temporal and spatial resolution, in order to be appropriate for simulation in urban drainage models.

Since the renewal rate of pipes in the existing urban drainage system is relatively slow, emphasis must lie not only on city development but also on future climate change. Design criteria, therefore, need to be changed according to changes in precipitation.

Future research is necessary to investigate the effect that differences in precipitation and temperature changes in different parts of Sweden will have on urban drainage and urban water management. Also, more focus on adaptation strategies to find methods to gradually adapt the system and infrastructure with the best environmental and economical aspects is needed. Weak spots in the system must be identified for the adaptation to be as effective as possible. Knowing when, where, and how to put the correct measures when adapting the urban drainage systems is essential for efficient management.

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Paper I

Adaptation of RCA3 Climate Model data for the specific needs of urban hydrology simulations

Jonas Olsson, Mats Olofsson, Karolina Berggren, Maria Viklander

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I

ADAPTATION OF RCA3 CLIMATE MODEL DATA FOR THE SPECIFIC NEEDS OF URBAN HYDROLOGY SIMULATIONS

by

J. Olsson[1], M. Olofsson[2], K. Berggren[2], M. Viklander[2]
[1] *SMHI, FoUh, Norrköping, Sweden (Jonas.Olsson@smhi.se)*
[2] *Luleå University of Technology, Dep. of Civil and Environmental Engineering, Luleå, Sweden (Mats.Olofsson@ltu.se, Karolina.Berggren@ltu.se, Maria.Viklander@ltu.se)*

ABSTRACT

Adapting climate model data to urban drainage applications can be done in several ways but a popular way is the so-called 'delta change' method. In this method, relative changes in rainfall characteristics estimated from climate model output are transferred to an observed rainfall time series, generally by multiplicative factors. In this paper, a version of the method is proposed in which these 'delta factors' are related to the rainfall intensity level. This is achieved by calculating changes in the probability distribution of rainfall intensities and modelling the delta factors as a function of percentile. The model is applied to 30-min output from the RCA3 regional atmospheric climate model, in a grid box covering Kalmar City, Sweden. The climate model results indicate an increase of the highest intensities by up to ~20% and a decrease of lower intensities by up to almost 40%. This result is valid for a 30-min time scale, and to evaluate whether urban drainage impact assessment can be meaningfully performed on this time scale, a MOUSE model was applied in Kalmar using different time steps. The results indicate that a 30-min time step may be meaningful, but that ways to transfer the rainfall changes also to data of a higher time resolution needs to be considered. This will be done in future studies, as well as further testing and evaluation for other Swedish cities.

Keywords: urban drainage, precipitation, regional climate model, climate change, urban hydrology

1 INTRODUCTION

With a changed climate especially future high intensity rain will cause problems such as flooding because of limitations in the existing urban drainage system. Identification of weak spots in the existing system and modifications of the design criteria is needed in order to achieve a future sustainable urban water management. In many cities in Sweden, the rate of renewal of pipe systems is very low today, but it is likely that renovation activities will increase. The planning, design and operation of the future urban drainage system must take the climate change into account. According to the results from SWECLIM (Swedish Regional Climate Modelling Programme), it is possible that the precipitation during the winter will increase as much as 30 to 50% by the year 2100. Summer precipitation is likely to decrease in the southern and mid parts of Sweden, but the northern part can expect an increase in precipitation even during the summer (Bernes, 2003). Transferring change in rain characteristics from climate precipitation models to urban drainage models is essential to find out how the precipitation change will affect the urban drainage system. This paper investigates a modification of the delta change method to transfer the change to an observed gauge data series in the City of Kalmar in Sweden. Kalmar was selected as a suitable study area because a calibrated MOUSE model from an urban area was available.

The objective of the study is to find a method to adapt or transfer climate model precipitation data for use in an urban drainage model. The results will enable more precise urban hydrology climate change simulations, and thereby more precise adaptation strategies for the urban drainage systems.

2 CLIMATE MODEL PRECIPITATION DATA

In Kalmar, high rainfall intensities mainly occur during July and August, while there are somewhat fever high intensity rains in June and September. This study focuses on the summer period (June-August) as autumn, winter and spring rains will be examined in upcoming studies. The assessment of the climate change impact on future rainfall was based on output from the regional atmospheric climate model RCA3, developed at the Rossby Centre, SMHI (Kjellström et al., 2005). The RCA3 model was recently applied for a 140-year transient climate simulation from 1961 to 2100. In this experiment, the RCA3 model downscales the output from the global climate model ECHAM4 (Roeckner et al., 1996) to a 50×50 km spatial resolution over northern Europe. The two main emission scenarios, SRES A2 and SRES B2 as defined by UN IPCC in Nakicenovic et al. (2000), were run. For this study, 140-year time series of 'total precipitation' (P) from the RCA3 output from the model grid square covering Kalmar city was extracted. The P data were available with a 30 min temporal resolution, which is higher than in most previous climate change analyses and makes an assessment of changes in short-term rainfall properties with some confidence possible.

Within the total 140-year period, four 30-year sub-periods were selected to represent different climate perspectives: 1971-2000: today's climate (TC), 2011-2040: near-future climate (FC1), 2041-2070: intermediate climate (FC2), 2071-2100: distant-future climate (FC3). This sub-period division corresponds to other investigations of hydrological climate change impact assessment made at SMHI.

2.1 Model data validation

The RCA3 data was compared with a quality controlled 14-year time series (1991-2004) of tipping bucket rainfall observations from Kalmar (Hernebring, 2006). In terms of accumulated volume, RCA generates ~70% more precipitation than the observed amount during the period. However, it should be noted that tipping-bucket gauges generally underestimate the long-term volume, and indeed Hernebring (2006) found that the daily SMHI gauge in Kalmar recorded ~25% more precipitation than did the tipping-bucket gauge. This indicates that the actually observed volume is higher. Still RCA3 overestimates this amount, mainly owing to a too high frequency of very small intensities. The percentage of dry periods (i.e. P=0) is 95.8% in the observations but only ~51% in the model output. A lower percentage is expected in the model data as they represent a spatial average. However, also in comparisons with spatial observations the RCA3 model has been found to overestimate the frequency of low intensities. Thus model inaccuracy is most probably also contributing to the underestimated frequency of dry periods. As a consequence of this underestimation, the mean intensity for wet periods (i.e. P>0) is almost five times lower in the model output than in the observations.

Concerning maximum intensity, in the RCA3 data it is 3.3 mm whereas in the observations it is 15 mm. Point and areal precipitation values are often related by so-called areal reduction factors (ARFs), which specify how much a point value is reduced when considering an area surrounding the point location. In NERC (1975), the recommended ARF for a duration of 30 min and an area of 3000 km² is 0.41. A point value of 15 mm would thus reduce to ~6 mm for an area of the size of the RCA3 grid, which is still more than the RCA3 maximum. However, the observed value 15 mm is indeed extreme. The second to fourth highest maxima are all ~10 mm, corresponding to an areal value of ~4 mm which is reasonably similar to 3.3 mm. Another reason for the underestimated extremes is most probably limitations in the physical description of rainfall generation in the RCA3 model.

Overall the RCA3 model results appear to reasonably well reproduce the features of the observed precipitation. It may be remarked that much of the inaccuracy in the model results is related to the smallest intensities, which have little significance in the context of urban flooding.

3 METHODOLOGY

In principle, there are two ways to use the climate model precipitation data. One is to use it directly as input in the MOUSE model. However, in light of the scale mismatch between climate model results (50×50 km, 30 min) and MOUSE input observations (point value, minutes), advanced transformation of the climate model results is conceivably required. Another common way is to use the climate model results to identify future relative changes in the precipitation pattern, and then transfer these changes to the available observations. This approach is known as 'delta change' (e.g. Hay et al., 2000), which is a widely used method to transfer the signal of climate model output to hydrological model input (e.g. Andréasson et al., 2004). In principle, relative changes found in climate model simulations are transferred to a time series of rainfall observations. In its simplest form, all non-zero observations are simply scaled up or down by the percentage increase or decrease (delta-factor) found in the climate model results for a certain future period, preferably on a monthly or seasonal basis. In more elaborated versions, different delta factors have been used for low and high rainfall intensities (Semadeni-Davies et al., 2005).

In principle, delta change should only be applied to observations of the same temporal and spatial scale as the climate model output, i.e. 30 min and 2500 km² in our case. However, in practice often much higher-resolution rainfall observations are modified by delta-factors obtained from lower-resolution climate model output. Thus an assumption must be made that future lower-resolution changes in rainfall are equal or at least similar to the future higher-resolution changes. In terms of maxima, the validity of this assumption depends on the future changes in rainfall generating mechanisms. Lower-resolution (long-term, large area) maxima are often produced by large frontal-type rainfall systems, whereas higher-resolution maxima (short-term, point value) are produced by local convective systems. The latter process is, however, not possible to properly describe in climate models owing to the spatial model resolution. Thus it is likely that the future rainfall changes found in climate model results mainly reflect changes related to large-scale rainfall-generating systems. Applying these changes to a point-value time series is therefore inevitably associated with an uncertainty.

Concerning the temporal structure of rainfall events, a distinct advantage of the delta change method is that a realistic structure is preserved, which may not be the case if using model data directly. A limitation, however, is that the duration of rainfall events, and thus the number of wet periods, is assumed constant. In our case this assumption appears reasonably well fulfilled, e.g. as the percentage of dry periods remains fairly constant around 50%. Further, in the context of urban hydrology, it may be assumed that changes in (high) rainfall intensities are more important than changes in rainfall occurrence, which is largely influenced by low-intensity periods.

In the present study, the delta change method has been applied in a percentile-based version. This allows the delta-factors to vary continuously with intensity level.

4 RESULTS AND DISCUSSION

4.1 Delta change

The percentiles of the rainfall intensity distributions (the 3000 highest intensities) of each climate perspective (TC, FC1, FC2, FC3) were calculated. Within each 30-year perspective, a mean distribution was calculated by averaging the percentiles obtained from the first, middle and last 10-year period, respectively. As an example, Figure 1a shows the distributions obtained for TC and FC3 in emission scenario A2. The 10% highest intensities increase, whereas the 90% lowest intensities decrease. From curves such as in Figure 1a, percentile-related delta-factors were calculated as the ratio of a certain percentile in the future climate to the same percentile in today's climate. Figure 1b shows the resulting delta-factors for emission scenario A2.

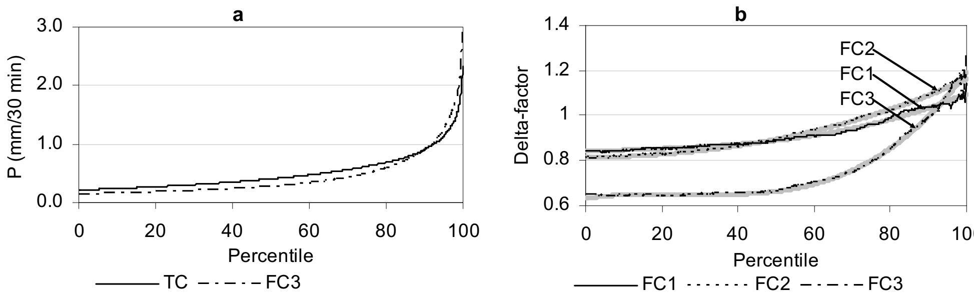

Figure 1 – Percentiles of the rainfall intensity distributions of climate perspectives TC and FC3, scenario A2 (a) and Calculated delta-factor distributions (black lines) and fitted third-order polynomials (grey lines), scenario A2 (b).

For FC1 the factors range from 0.85 (i.e. a 15% decrease) for the lowest intensities, to 1.14 (14% increase) for the highest intensities. For FC2 the range is 0.81-1.19 and for FC3 0.65-1.27. Whereas FC1 and FC2 are overall relatively similar, the result for FC3 is substantially different. For all percentiles except the very highest, the FC3 delta-factors are distinctly lower, reflecting a remarkable future decrease in total summer rainfall. To smooth out the fluctuations for the highest percentiles, which are expected as they are derived from high and extreme rainfall intensities, and also to facilitate application of the delta-factor distribution to observed time series, third-order polynomials were fitted to the delta-factors, as shown in Figure 1b. The R^2 of the fits is typically ~0.99. The fitted delta-factors corresponding to the highest percentile are 1.10 for FC1 (1.14 for the original, non- smoothed delta-factors), 1.16 (1.19) for FC2 and 1.19 (1.27) for FC3. Thus the increase of the highest intensities is slightly lower in the polynomial fits, but on the other hand fitted delta-factors for intensities just below the maximum are often higher than the original factors.

For emission scenario B2, the range of calculated delta-factors is 0.88-1.48 for FC1, 0.94-1.36 for FC2 and 0.88-1.52 for FC3. In this scenario FC2 stands out with generally higher delta-factors, reflecting an increase in total summer rainfall. As for A2, third-order polynomials provided accurate fits which slightly underestimated the delta-factors related to the very highest percentiles.

Application of the derived delta-factor polynomials to an observed time series, e.g. tipping-bucket data aggregated to 30-min resolution, is straight-forward. From all rainfall intensity values in the time series, percentiles are calculated. Then, for each value, the corresponding percentile is identified, the delta-factor estimated from the polynomial fit, and the value adjusted accordingly. In principle, the method can be applied also on a higher time resolution, e.g. by applying the estimated 30-min delta factor to all registrations within the 30-min period.

Figure 2 shows an example of how observations are modified by the delta change method. Typically, high intensities in the centre of an event increase whereas the preceding and succeeding low intensities decrease.

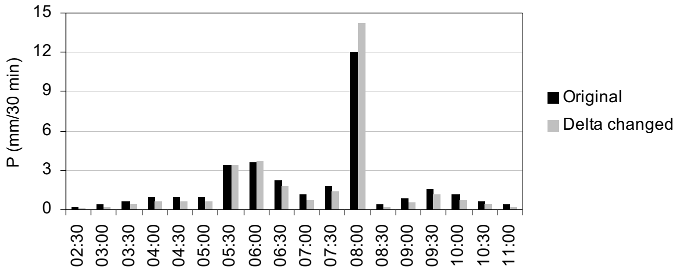

Figure 2 – A sequence of 30 min rainfall intensities, observed (black) and modified by delta change for FC3, A2 (green).

4.2 Urban drainage modelling

The DC method here applies for a 30-min time scale, this time scale is however generally seen as to large in urban drainage modelling. To evaluate whether urban drainage impact assessment can be performed on this time scale, the Kalmar urban drainage model was run with 5 min and 30 min time step data for different rain events. Results show that the number of manholes where flooding occurred is about 30% lower with 30-min data for very high intensity rains, like the flooding that occurred in Kalmar 2003 with a 5 min intensity of 403.3 l/s, hectare and a 30 min intensity of 230.4 l/s, hectare (Hernebring, 2006). For lower intensity rains the differences in water levels are smaller. This is of course different for different systems but the need for 5 min data depends on how accurate the model and how accurate the precipitation data are.

It is also necessary to raise the question if delta-change or dissagregation is necessary since the future climate data is a model predicting future situations. Similar results may be obtained by using simpler methods like applying a multiplicative factor on the observed data set or running 30 minute model data in the runoff model without further dissagregation. This needs to be studied more thorough but the quick study above indicates that 30 min data can be used in an urban drainage model if comparison analysis has been made with other time resolution and as long as it is kept in mind the disadvantages of a 30 min series. It is likely that long term change in water levels can be investigated with 30 min data while high intensity rains require a smaller time scale. Since 30 min model data is available for a 140 years span it would be useful to run the data untouched to find out whether the number of floods will increase and if it will be in the same quantity as in the delta-change method. Some initial processing on the model data for example with a threshold value might be needed to remove some of the wet periods. These comparisons will be made in a later project.

5 CONCLUSIONS

It was concluded that the proposed percentile-based version of the delta change method appears suitable for transferring the rainfall changes found in climate model data to an observed time series, specifically the trend with increased maximum intensities but decreased total volume during summer. By this approach, the structure of individual rainfall events are modified, typically by an increase of interior maximum intensities and a decrease of the surrounding lower intensities. This method provides more realistic results than the standard delta change method based on a fixed change of all intensities. Further evaluation will be made and the results used for urban drainage modelling in several Swedish cities.

The numerous uncertainties involved must, however, be emphasized. As in all climate change impact studies, there are the issues of how accurate the climate model is and how realistic the scenarios are. In urban drainage applications there is further the issue of mismatching scales. In the present study we use 30-min model output, which is a step towards urban scales compared with previous work, but in terms of spatial scale there is a big gap between the model resolution and the urban drainage process. Future work will focus on downscaling the climate model output to fit urban drainage modelling, e.g. by sophisticated statistical methods. The long-term aim is to be able to directly use downscaled model output in an urban drainage model.

6 ACKNOWLEDGEMENTS

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Paper II

Tools for measuring Climate Change Impacts on Urban Drainage Systems

Karolina Berggren, Mats Olofsson, Maria Viklander, Gilbert Svensson

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Tools for Measuring Climate Change Impacts on Urban Drainage Systems

Les outils de mesure des effets du changement climatique sur les systèmes d'assainissement pluvial urbain

Berggren K.[1], Olofsson M. [1], Viklander M. [1], Svensson G. [1]

Luleå University of Technology, SE-971 87 Luleå, karolina.berggren@ltu.se; mats.olofsson@ltu.se; maria.viklander@ltu.se; gilbert.svensson@ltu.se

RESUME

Le changement climatique, par exemple des événements pluvieux plus intenses, aura un effet sur les systèmes d'assainissement pluvial urbain et causera des problèmes dans les grands centres municipaux. Il y a un besoin de mieux comprendre et évaluer les effets et les conséquences; donc une stratégie et les outils possibles sont suggérés dans cet article. Les outils recommandés sont les Simulations d'assainissement Pluvial Urbain, un Rapport de Sûreté, et un Système d'Information Géographique (SIG). Puisque les effets des changements climatiques sur les systèmes d'assainissement pluvial urbain concernent plusieurs domaines, l'évaluation devra être effectuée en coopération avec, par exemple des experts en assainissement pluvial urbain, en changement climatique, des praticiens, des politiciens, etc.

ABSTRACT

Climate change, e.g. more intense rainfall events, will affect urban drainage systems, and cause problems in cities. There is a need to understand and assess these impacts and consequences better; therefore, a strategy and possible tools are suggested in this paper. The recommended tools are Urban Drainage Simulations, Risk Analysis, and Geographic Information Systems (GIS). Since the impacts of climate change on urban drainage concerns several different disciplines, the assessment should be performed in cooperation with, e.g. urban drainage experts, climate change experts, practitioners, politicians, etc.

KEYWORDS

Climate Change; GIS; Risk analysis; Urban Drainage; Vulnerability

1 INTRODUCTION

The global mean temperature has increased during the last hundred years according to IPCC (2001), consequently changing the hydrological cycle. In recent years we have seen weather considered by many as “extreme weather events”, but what will be the consequences if these events occur more often in the future? Technologies for urban drainage have been developed over a long period of time, though design criteria have been relatively constant throughout the major urbanisation era. As a consequence, changes in climatic conditions, such as increasing rain intensities and changing snowmelt patterns, and more extreme weather events, such as thunderstorms, will most likely create problems in cities. The issue of climate change and urban drainage has previously been emphasised in studies concerning integrated urban drainage planning (e.g. Semadeni-Davies et al., 2006; 2004; Ashley et al., 2005; Waters et al., 2003) and on climate change and urban water considering flooding and risks (e.g. Evans et al., 2004). A study from the UK has shown, for example, that the potential effects of climate change on urban property flooding are likely to be significant (Ashley et al., 2005).

According to an investigation by the Swedish Meteorological and Hydrological Institute (SMHI) in 2004/2005, very few Swedish sectors had strategies for adaptation to climate change, and among those measures already taken, the majority were adaptations to the existing climate and not the future (Rummukainen et al., 2005). Some things have happened since then, e.g. the establishment of a national group of experts in drinking water supply and leadership during crisis (VAKA, started in 2005) and a vulnerability investigation was set up by the Swedish government, which recently presented part time results regarding the vulnerability of society due to climate change (SOU, 2006).

Still, there is a need for more knowledge to successfully adapt society. For the area of urban drainage, there is also a need for better and updated tools and strategies to assess the impacts and to feasibly adapt the system. For this reason, the aim of the study is to investigate the possible impacts concerning urban drainage systems and future climate change, and in more detail, to find and recommend a strategy and tools that can be used for this purpose.

2 METHOD

This work has been carried out as a literature study together with simulations using an urban drainage model (Mike Urban/MOUSE by DHI), as well as discussions with representatives from different disciplines, e.g. Water and Wastewater engineers, in order to develop a useful strategy for climate change impact studies in urban areas.

3 RESULTS

The strategy to investigate the climate change impact on urban drainage has for this research project been designed as shown in Figure 1, where the boxes marked with bolder lines are the main focus for this particular study and the other boxes represent the overall approach. SMHI has provided precipitation data from the regional atmospheric climate model (RCA3, developed at the Rossby Centre, SMHI (Kjellström et al., 2005)), originating from the global circulation model ECHAM4 and future scenarios SRES A2 and B2 (defined by UN IPCC in Nakicenovic et al. (2000)), which are intermediate (not extremely high or low). These results have been used for local climate projections for the municipality of Kalmar, southern Sweden, and further transferred from areal to point rainfall via the Delta Change method, previously used in the urban environment by, e.g., Semadeni-Davies et al. (2006), and later improved and adjusted for this particular study by Olsson et al. (2006). The point rainfall data have the form and pattern as tipping-bucket rainfall data, and were used as input to the urban drainage simulations carried out with Mike Urban (MOUSE) by DHI. The urban drainage simulations combined with risk analysis methodology and Geographic Information Systems (GIS) will improve the impact assessment for the urban drainage system. These impacts will undoubtedly have consequences for the city as a whole. When a municipality gains knowledge of weak and sensitive areas in the system and the city this way, it may be easier to choose and prioritize between adaptation strategies.

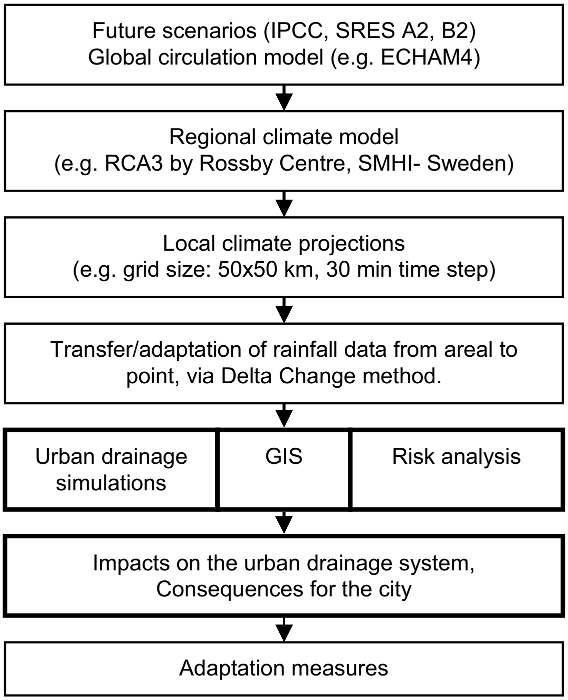

Figure 1. The overall strategy for this research project, which aims at investigate climate change impacts on urban drainage systems and the consequences for the city, where the boxes marked with bolder lines are the main focus of this article.

3.1 Urban Drainage simulations

Several different types of urban drainage simulation tools are available, e.g. Mike Urban (MOUSE), SWMM, Infoworks etc. Many researchers have used these tools to describe the impacts of both climate change and urbanisation (e.g. Semadeni-Davies et al., 2006; Ashley et al., 2005; Waters et al., 2003) and can give information about future conditions, provided that it is used appropriately and the model is calibrated for the specific system. The model can, for example, provide information about water levels in nodes and links, frequency of floods indicating weak spots in the system and city, and consequently pinpoint where more resources are needed. Water level durations in nodes can also be compared in the model for future conditions, indicating how the duration of floods may increase, and connected with a model for surface runoff to give more precise information on where problems will occur. Different scenarios for future changes in city characteristics, e.g. increase of impervious areas, help to analyse the impacts of city change on urban drainage. Water level output results from model runs can be inserted into a GIS and compared with more data sources, such as infrastructure, economic and environmental values. Calculating the economic cost for specific areas produces a vulnerability map showing reasons for improvement of the sewer system or building of rerouting possibilities to areas with less economic/environmental value.

Lindsdal, a suburb of Kalmar, was used as a reference area in a pilot study. According to results from SWECLIM (Swedish Regional Climate Modelling Programme), precipitation in Sweden during the winter will possibly increase by as much as 30 to 50% in the future. Summer precipitation in southern Sweden is likely to decrease in amount, but become more intense, whereas northern Sweden can expect an increase in both intensity and amount (Bernes, 2003).

Details about the Lindsdal area: 410 nodes, population 3,000, size of the contributing catchment areas 54 ha and amount impervious area 20 ha. To decrease the data volume for the long simulation time, 120 nodes were selected as representative for the system. The urban drainage model (separated, only stormwater) has run with four different rainfall series, representing today's climate (TC), near future climate (FC1: 2011-2040), intermediate future climate (FC2: 2041-2070), and distant future climate, (FC3: 2071-2100). The original tipping-bucket rainfall series (Hernebring, 2006) for TC has been transformed by the Delta Change method described in Olsson et al. (2006). Figure 2 shows how the number of flooded nodes (water level exceeds ground level) in the system will increase in the future.

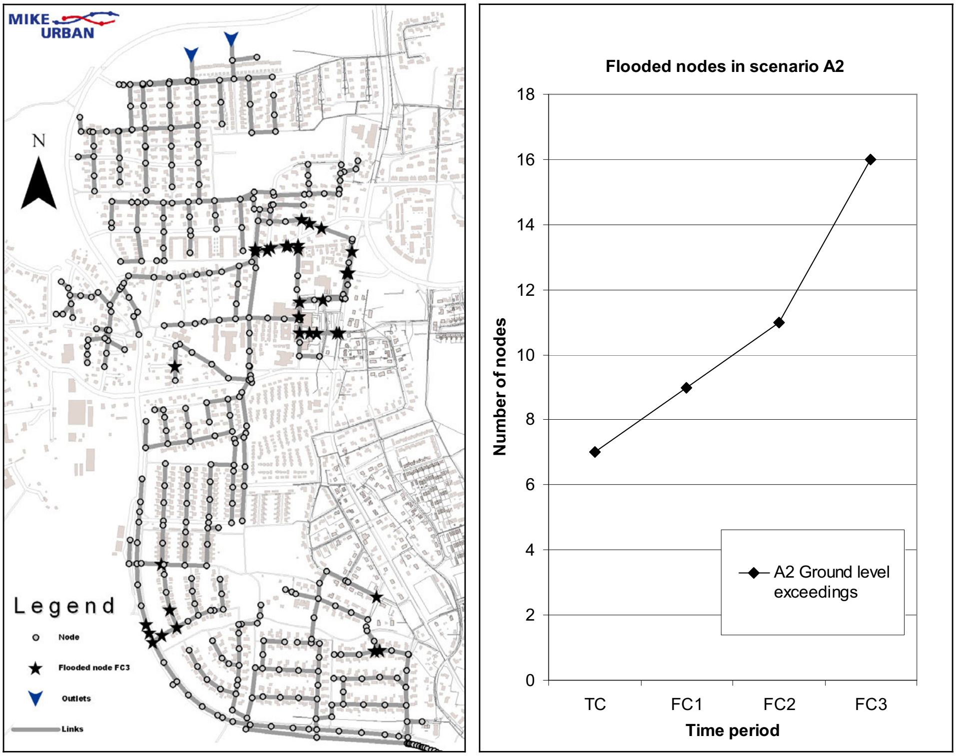

Figure 2a, Lindsdal area; flooded nodes in time period FC3. Figure 2b, Number of nodes where ground level was exceeded in the different time periods.

3.2 Risk Analysis

A definition is needed whenever speaking about risks, as the word has been used in the literature to mean either probability of danger or the hazard itself (SCOPE, 1980). Christensen et al. (2003) summarised the most important risk definitions (including material from, e.g. EU, UN/OECD, US-EPA and ISO guidelines) and the actions taken to assess risk. Risks can easily be presented by answering three questions: *1) What can happen? 2) How likely is it to happen? 3) If it happens, what are the consequences?* (e.g. Ljungquist, 2005), which may also be presented as a cause-effect relationship (Christensen et al., 2003). Hauger et al. (2003) suggest that the concept of vulnerability should be used with the concept of hazard in an urban drainage risk assessment approach. Hazard assessment can be, e.g. frequency of extreme weather events; vulnerability assessment is more site specific and can be, e.g. the amount of damage to a specific house due to flooding.

There are several methods for risk analysis, and what to use depending on, e.g. the detail requirements, the objectives of the study, and the available resources. At the beginning of a project, it is recommended to start with a rough methodology to gain an overview. Both qualitative and quantitative methods are included in most risk analysis. A weakness in using deterministic or probabilistic methods, where the deterministic approach is based on consequences (worst-case scenario etc) and can be easy to conduct and communicate, is that problems can arise if there is no probability check, such as too many resources can be laid on events that are very unlikely to occur, etc. The probabilistic approach is based on risk, and uses both probability and consequences, but its drawback is the resource demand and the uncertainty connected to probability estimation (Davidsson, 2003).

Future precipitation in Sweden will increase in intensity and in amount (especially in the north) (Bernes, 2003), which inevitably will impact urban drainage systems and cities. Table 1 summarises examples of possible impacts in different parts of an urban drainage system due to high intensity rain events (as a cause-effect relation, where the risk source is the intense rainfall). However, this is not a complete summary and should only indicate the possible impacts in different parts of the system. There is also of course a need to make this table more detailed for the specific place of study, since the local conditions are very important and should preferably be performed in cooperation with both climate and urban drainage experts and those working more practically with the system, e.g. in a municipality. Local conditions can be highlighted for a large amount of people, which could be a good way to start working with any type of question requiring development and improvements of the organisation, infrastructure, etc. These types of studies may also gain a better understanding if used as a complement to other tools in a GIS.

Combined system	▪ If the sewer system has too low a capacity, the water level in the system can *cause basements to be flooded* ▪ Increased amount *of combined sewer overflow (CSO),* which can cause environmental problems concerning the receiving waters and also jeopardize the drinking water sources ▪ If the ground water level rises because of a higher amount of precipitation, more ground water will *infiltrate into the pipes*, and thus decrease the capacity of the system
WWTP (combined system)	▪ At a wastewater treatment plant, during times of high flows, *dosages of chemicals* for the processes can become unnecessarily high ▪ Increased amount of urban *polluted runoff* can reach to the treatment plant, which will cause more pollutants, e.g. heavy metals, in the sludge.

Pump stations	▪ Pump stations can easily become flooded as they often are located in low-lying areas. There is then a risk of getting *pipe surcharge* in the system if water is damming up backwards in the system ▪ Increased amount of *pump station sewer overflow*, which can cause environmental problems concerning the receiving waters and also jeopardize the drinking water sources
Separate system (only storm water)	▪ If the system has too low a capacity, the water level in the system can cause *surfaces in a city to be flooded* ▪ If the ground water level rises because of a higher amount of precipitation, more ground water will *infiltrate into the pipes*, and thus decrease the capacity of the system ▪ Heavy precipitation over urban areas can cause a *rapid runoff and wash of urban surfaces* and thus higher concentrations of pollutants, e.g. heavy metals to BMPs or receiving waters
Storm water pond	▪ At storm water ponds, the amount of *sediment losses* during heavy rain may increase if the pond is insufficient dimensioned, and there are no by-pass facilities. Thus polluted sediments may reach the receiving waters.
Infiltration basin	▪ The *infiltration capacity may decrease* if the ground water level rises, and cause, for example, *surface flooding*

Table 1. Examples of impacts in urban drainage systems during high intensity rainfall events.

4 DISCUSSION

4.1 Economic valuation

To serve as a useful and practical decision-making tool, most methods need to have an economic valuation included. Placing an economic value on an infrastructure might be realistic, but how will health aspects, nuisance from basement floods, closed roads, longer travel time, etc. be valued? An economic evaluation is, however, necessary to choose whether it is worth protecting a possible event from occurring. When different input is used in a GIS the vulnerability and possible damage on real estate and other areas can be assessed depending on the data from drainage models, infrastructure, real estate, demographic data, soil layers, future city plans, political economy, social factors, repair costs for different damages and areas, etc. The economic cost for affected areas can be identified, e.g. via a Cost–Benefit approach. A cost analysis can be made by a so-called raster- or vector analysis, depending on the available data, and show where it is most efficient to adapt the urban drainage system to maximise the future benefit, where this benefit is seen as a value of something not being flooded. This will support policy and decision-making of how to manage the urban drainage system in a time of climate change.

4.2 Cooperation

Risk and vulnerability analysis always needs to be done in cooperation with the parties concerned, since most problems involve several different disciplines. One big challenge in the urban drainage system is the close multiple interactions that exist, both within the system and related to city infrastructure. Dialogue with experts and politicians should also take place to make the most of the results and precautions should be taken, especially since climate change is a very uncertain area to base decisions upon.

4.3 Uncertainty

Climate change modelling is generally considered as very uncertain, and it is not possible to give an exact probability of future change. There are several uncertainty levels, e.g. data/parameter uncertainty, model/structure uncertainty, variability, and outcome uncertainty (e.g. Christensen et al., 2003). However, the scenarios used give a range in which the results can vary. It is common to use this as a measure to consider future trends. How useful it is can only be shown by the future itself. Urban drainage simulations represent one type of model uncertainty in this study and the results should always be interpreted with some caution. This model is, however, previously calibrated for this specific area, and may serve well especially for present and near future climate runs if assuming that no urban development activities will occur in that time. Uncertainty of the variability and the outcome of the project may be reduced if a dialogue and common sense are used.

4.4 Other aspects

As always, there are many other factors affecting the performance of the urban drainage system, e.g. impacts from the surrounding areas, water courses, sea level, etc., and the amount of impervious areas, which may increase with increasing population and new developments (e.g. Semadeni-Davies, 2006). There is also an aspect concerning the life expectancy of pipes and facilities (e.g. BMPs, WWTP etc), where pipes may be one hundred years or older and still be in operation (previously discussed by, e.g. Waters et al., 2003). In addition, the system will be more sensitive to extreme weather events and climate change factors if the capacity is decreased, e.g. if the pipe system is perforated and filled by roots, extra sand and sediment in the pipe system (e.g. originated from anti-skid measures), pipes are damaged and deteriorates, and other more temporary events, e.g. ice-blockages at the inlets. Through GIS analysis the results from combining factors are shown and each aspect can be valued, considered and analysed, thus increasing the knowledge and making it easier to suggest adaptation strategies for the urban drainage system to minimise the vulnerability of affected areas. When adapting to the future climate, it is also wise to keep updated in the field and adapt the urban drainage system step by step to gain knowledge with time and to invest available resources in the right places.

Plans for future research within this project are to compare different municipalities (different climate characteristics, and climate change) in Sweden, to consider the influence of sea, watercourses and ground water on urban areas, and to use risk analysis methodology and GIS to get a more holistic approach to climate change impacts assessment.

5 CONCLUSIONS

The strategy used to increase the understanding should be used in combination with different tools available (urban drainage simulations, risk analysis, GIS, etc.) and in cooperation with parties concerned, (urban drainage experts, climate change experts, practitioners, politicians, etc.), since most problems concern several different disciplines and a multifunctional understanding.

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Paper III

Hydraulic impact on urban drainage systems due to climate change

Mats Olofsson, Karolina Berggren, Maria Viklander, Gilbert Svensson

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III

Hydraulic impact on urban drainage systems due to climate change

Mats Olofsson*, Karolina Berggren, Maria Viklander, Gilbert Svensson

Division of Architecture and Infrastructure,
Luleå University of Technology, S-971 87 Luleå, Sweden
**Corresponding author, e-mail: mats.olofsson@ltu.se*

Abstract

Hydrological changes, particularly heavier precipitation due to an increasing global mean temperature, will very likely occur in the 21st century. These changes will have a great impact on urban environments and infrastructures, especially urban drainage systems whose capacities are closely related to rainfall events. The objective of this paper is to investigate the hydraulic impacts on an urban drainage network due to climate change. The paper is divided into two steps: (1) investigating model simulations' output from different rainfall series by comparing temporal and spatial resolutions and (2) comparing urban drainage impacts from today and in the future. The focus is on separate storm water systems, with a city in the south of Sweden being used as a reference study. Results from urban drainage simulations identify hydraulic impacts in the system, with help from parameters such as maximum water levels in nodes, pipe flow ratio, duration of floods, number of floods, and the frequency of floods in the system. In addition, both the ground level and a critical level below ground (-0,5 m) have been used to indicate the system's capacity. The urban drainage model simulations with input rainfall data from three sources (representing point rainfall with high time resolution, point rainfall with 30-min time step, and climate model data with high time and spatial resolution) showed that the specific needs for urban hydrology require high temporal and spatial resolution. This led to the climate model adaptation using a Delta change method in order to transform the tipping bucket rainfall series to represent future climate situations. Four time periods have been used in the investigation: today's climate (TC), near future climate (FC1: 2011-2040), intermediate future climate (FC2: 2041-2070), and distant future climate (FC3: 2071-2100). The maximum water levels in the nodes were significantly higher for future time periods compared to today's, for both climate scenarios A2 and B2. The number of flooded nodes in today's climate increases for future time periods (FC1, FC2, FC3) for both scenarios A2 and B2, as does the geographical distribution of floods in the system. The tendency is that future precipitation will increase both the frequency and the duration of floods. There is an evident need to handle future situations in urban drainage systems and have a well-planned strategy in order to cope with future conditions. For future considerations, including renewal plans, dividing the system into security levels/classes, where the critical level below ground will give earlier indications of capacity failure, might be preferable.

Keywords: urban drainage, climate change, flooding, hydraulic performance

1 Introduction

The increasing global mean temperature has been a concern for several years, and even more recently as the last twelve years (1995-2006) featured eleven of the warmest years since 1850 (IPCC, 2007). Hydrological changes, particularly increased numbers of heavy precipitation events, will very likely occur in the 21st century as a result of higher global mean temperature (IPCC, 2007). This will have great impact on urban environments and infrastructures. The issue of climate change and urban drainage has previously been emphasized in studies concerning integrated urban drainage planning (e.g. Ashley et al., 2005; Semadeni-Davies, 2004; Waters et al., 2003; Niemczynowicz, 1989) concerning flooding and risks (e.g. Evans et al., 2004a,b). One study has shown that the potential effects of climate change on urban property flooding are likely to be significant (Ashley et al., 2005). Internationally, there is a growing need to assess the impacts of climate change and the ability of societies to adapt. The Stern Report (2006), for example, reviews the economic impact of climate change. In Sweden, a committee initiated by the Swedish government will present a report this year regarding society's vulnerability due to climate change (SOU, 2006).

Technologies for handling urban drainage have been developed over a long period of time, though design criteria have been relatively constant throughout the major urbanization era. Since the fifties, urban drainage recommendations have been to separate storm water (rain and snow melting) from wastewater (from households etc) in the sewer systems (Bäckman, 1985). But, as several cities are older than this, many urban sewer systems are often partly combined, especially in city centres (e.g. Butler & Davies, 2004) where it is also more expensive to rebuild and replace pipes. Increased rainfall intensities will most likely create problems in both types of systems: generally, basement flooding and sewer overflow (CSO) will occur in the combined system and surface flooding will occur in the separate storm water system.

There are several approaches to assessing impacts in urban drainage systems due to climate change, but a common way is to perform model simulations of urban drainage systems (e.g. Semadeni-Davies et al, 2006; Ashley et al, 2005; Waters et al, 2003), using different models (e.g. Mike Urban/MOUSE, InfoWorks, SWMM). A problem connected to this approach is the input of rainfall data, because the translation of climate model rainfall for urban applications/usage can be problematic as the climate change rainfall data apply to rainfall of low spatial resolution (e.g. 50*50 km), whereas the urban rainfall data apply to point rainfall. Another problem is the climate model's description of intensity and extreme weather events, which are not very well reproduced, especially for the intensities and patterns of heavy rainfall and extreme events (IPCC, 2001). There might also be problems when describing and analysing the results of the urban drainage simulations in terms of which parameters to use to describe the impacts on the system.

1.1 Objective and scope

The objective of this paper is to investigate the hydraulic impacts on an urban drainage network due to climate change. The paper is divided into two steps: (1) investigating model simulations' output from different rainfall series by comparing temporal and spatial resolutions and (2) comparing urban drainage impacts for four different time periods – today, near future, intermediate future, and distant future (2100). This investigation will be performed as a case study of a city in the south of Sweden. The focus of this paper is on separate storm water systems, a system that is also the common design standard for new systems in Sweden. The principles may still be of use for combined systems, in a slightly modified manner.

2 Method

The method is to describe the technical impacts on urban drainage systems due to climate change with model simulations of urban drainage systems using climate model data and existing tipping bucket data.

2.1 Precipitation data

Two kinds of precipitation data have been used: existing tipping bucket data and climate model data.

2.1.1 Measured rainfall data

The rainfall measurement from the study area was tipping-bucket data with 0,2mm resolution summarized in Hernebring (2006). From the total series of data (1991-2004), the time period 1993-2002 was selected due to an extreme weather event that occurred in 2003. This extreme event included, for example, a rainfall event corresponding to a return period of 46 years.

2.1.2 Climate model data

SMHI (Swedish Meteorological and Hydrological Institute) has provided precipitation data from the regional atmospheric climate model (RCA3, developed at the Rossby Centre, SMHI (Kjellström et al., 2005)), originating from the global circulation model ECHAM4 and future scenarios SRES A2 and B2 (defined by UN IPCC in Nakicenovic et al. (2000)). The scenarios are intermediate (not extremely high or low) but still give a range of the future changes. Time resolution is 30 minutes, and spatial resolution is 50x50 km. Climate data from the 50*50km covering the study area show that summer precipitation will decrease in the summer but that the intensity will increase.

2.1.3 Modified precipitation data

Since climate model data has limited temporal and spatial resolution, the Delta change method is used to transfer climate model data to a rainfall series (similar to a measured rainfall series) for use in urban drainage models. The tipping bucket rainfall data preserves the time and spatial resolution. The intensity changes in amplitude according to future changes in climate. The original tipping-bucket rainfall series (Hernebring, 2006) for the study area has been transformed by the Delta change method described in Olsson et al (2006). Four different rainfall series represent the time periods: today's climate (TC: 1971-2000), near future climate (FC1: 2011-2040), intermediate future climate (FC2: 2041-2070), and distant future climate (FC3: 2071-2100). The change compared to today's climate (TC) in each future time period has been transferred via Delta change to the tipping-bucket rainfall data series (Olsson et al., 2006), as exemplified by Figure 1. The factors of change have been applied directly, which gave a better representation of the highest intensities than did the fitted polynomials. But, in order to decrease the risk for overestimation, the high intensity rain in 2003 was removed after the factors had been applied.

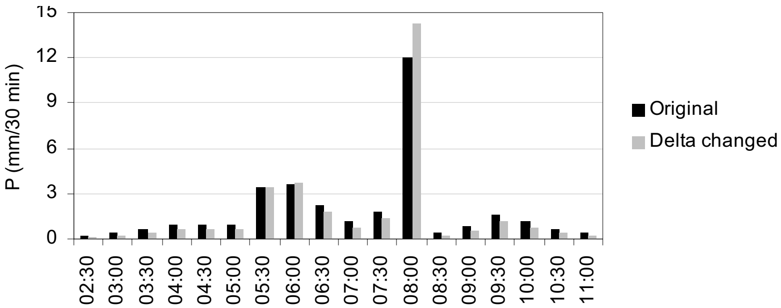

Figure 1. 30 min rainfall data, observed series in black and modified by Delta change in grey for FC3, A2. (Olsson et al., 2006)

2.2 Study area

The area of study is a small city in the south of Sweden, which has a population of 3 000 and a contributing catchment area of 54 ha, of which 20 ha is impervious. The urban drainage system has 410 nodes and is separated, thus it contains only storm water. The system is designed according to the current design standards (Svenskt Vatten, 2004), thus the system should manage rains of at least a 10-year return period without surface flooding. Since the time of construction, the system has been degraded and probably repaired and rebuilt as it generally is, but should still manage the design criteria.

2.3 Data model

The simulation model of the network is somewhat modified in Mike Urban (DHI, 2005) compared to the existing system and is used as an example, representing a common storm water system in a small town. Also, as this paper focuses on comparing the impacts from different time periods, the starting condition of the system is not highly important. To decrease the data volume for the simulation time, 120 nodes were selected as representative for the system for result output. The selection of nodes was based on the following criteria: (1) nodes representing swales were removed from the result file, (2) nodes with depths less than 1,0 m were removed from the result file, (3) if there were several nodes close to each other, only a few of them were kept to serve as representatives for that particular sub area. The system has three outlets, two shown in Figure 4 in the upper part and one in the lower east part.

2.4 Parameters

The following parameters are chosen in order to describe the impacts.

2.4.1 Maximum levels in nodes

Maximum water level in nodes is a measure used to describe differences between the time periods. The measure should be used as an indicator of the system's capacity, although the measure is somewhat simplified, as it does not consider whether or not water is exceeding ground levels.

2.4.2 Exceeded levels

Levels in the nodes are described as both the ground surface and a critical level which is set at 0,5 m from the ground level. The purpose of two levels of concern is to get a broader view of the water levels in the system in order to assess the security level in the system. The measure is used to describe differences between time periods and to describe tendencies. This measure may also be used in further calculations concerning consequences for the city, e.g. economical losses.

Number of nodes affected – describes in which nodes (and parts of the city) water is exceeding the ground or critical levels, thus indicating the capacity of the system.
Frequency – describes how often the levels in the nodes are exceeded, and describes which nodes (and parts of the city) are more often affected by water exceeding ground (or critical) levels.
Duration – describes how long water is exceeding the ground level, indicating the possibility of damage due to flooding. Time is measured both as the difference in duration within unique flood events and as a maximum duration for each time period.

2.4.3 Pipe flow-ratio

Pipe flow-ratio is the ratio of flow-rate (Q) and flow-rate full (Q_f). It measures the maximum flow-ratio for all time periods and indicates how much the maximum water flow in the pipe system will increase. This measure may be used as an indicator of the system's capacity; therefore, it will identify areas where the possibility of floods and subsequent damage is higher due to high pressure and water leaking from the pipes.

2.5 Statistical comparisons

Statistical analysis of the results has been performed as a comparison within matched pairs of experimental material (nodes), where the maximum levels in the time periods (TC, FC1, FC2, and FC3) are compared in the same node to figure out if a difference exists between time periods. This type of comparison is necessary due to the lack of homogeneity between nodes, which will contribute to the variability of the maximum level measurements and will tend to inflate the experimental error, thus making a true difference between time periods (TC, FC1, FC2, and FC3) harder to detect (Montgomery, 2001). The software used is MiniTab. The results will be presented as confidence intervals of the differences of maximum level in pairs, at a 95 % confidence level. There will also be a t-test analysis performed showing if the null hypothesis (there is no difference) will be rejected in favour of the hypothesis that there is a significant difference between the pairs at a 95 % confidence level.

3 Results

3.1 Spatial and temporal resolution in precipitation data

The main focus for this part is to address differences in urban drainage output results given from different types of input rainfall data. As the problem is concerned with climate model data and urban drainage applications, the comparison has been made from the two approaches: temporal and spatial. The input rainfall data compared is (1) tipping bucket rainfall data (TB), from the local area presented in Hernebring (2006)-collected over 10 years (1993-2002), as a point source rainfall data series, (2) climate model data (CMD), which is a projection of RCA3 on the local area of study, described in chapter 2.1, and (3) tipping bucket rainfall data from the original series, which were aggregated into 30 min time steps (TB30). This concept is also presented in Figure 2. The test parameter is maximum water levels in nodes, and the analysis has been made as a statistical comparison within matched pairs of experimental material (nodes) as described in the method.

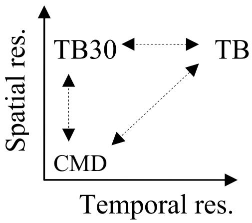

Figure 2. Principles of the comparisons of rainfall data, TB: Tipping Bucket, TB30: “Tipping Bucket” 30 min, CMD: Climate model data 30 min. The axes are spatial and temporal resolution of data.

The statistical analysis of the results verifies that temporal resolution has the greatest impact on urban drainage simulations. For this example, the importance of temporal resolution for urban hydrology is shown for maximum water levels in nodes, at a confidence level of 95 %. The t-test confirms that the difference is significant at a 95 % confidence level for the three comparisons (Figure 2). Tipping bucket rainfall data (TB) results in 0,25 - 0,42 m higher maximum levels in nodes, compared to a 30 min transformed rainfall series (TB30). In comparison, the impact of spatial resolution also shows a difference. The urban drainage impacts on maximum levels in the nodes are between 0,17 - 0,35 m higher for ”tipping bucket 30-min” data (TB30). Further, the difference between the original tipping bucket rainfall series (TB) compared to climate model data (CMD) is between 0,35 - 0,44 m higher for tipping bucket data, at a confidence level of 95%. Thus, the climate model rainfall data needs transformation before being appropriate to use in urban drainage model simulations.

3.2 Urban drainage impacts due to climate change

The main focus for this part of the paper is to compare the hydraulic impacts in urban drainage due to climate change. The input rainfall series used is the original tipping bucket rainfall data (Hernebring, 2006) for today’s climate (TC: 1993-2002), and the Delta changed tipping bucket rainfall data representing three future time periods (FC1: 2011-2040; FC2: 2041-2070; and FC3: 2071-2100) (according to Olsson et al, 2006). Scenarios A2 and B2 are also used for this approach.

The urban drainage test parameters for this approach are (1) maximum water levels in nodes, (2) number of nodes exceeding ground and critical levels, (3) frequency of nodes exceeding ground and critical levels, (4) duration of the floods when water in the nodes exceeds ground level, and (5) pipe-fill as flow-ratio (Q/Q_f).

3.2.1 Maximum water levels in nodes

For the comparisons of maximum water levels in nodes, the results show that maximum water levels in nodes are higher for all the future scenarios (FC1, FC2, and FC3) compared to today's (TC) levels, for both scenarios A2 and B2, at a confidence level of 95%. The t-test also confirms that there is a statistically significant difference for all the comparisons between time periods, at a 95 % confidence level. The maximum water levels in nodes for the near future time period FC1 compared to today's climate are between 0,10-0,16 m (A2) or 0,12-0,18 m (B2) higher. Confidence intervals for the differences are presented in Figure 3. The width of the confidence intervals for both A2 and B2 is about 0,05m for near future time periods (FC1-TC), increasing up to about 0,12 m for distant future time periods (FC3-TC).

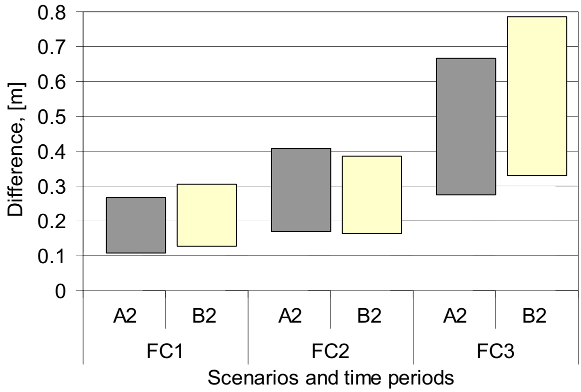

Figure 3. Difference in maximum water levels in nodes, 95% confidence interval for mean difference between today's climate (TC) and future time periods (FC1, FC2, FC3).

The t-test also shows that a comparison between scenarios A2 and B2, within the same time period, is not unambiguous. There is a significant statistical difference between A2 and B2, for the time period FC3 for maximum water levels in nodes, at a 95 % confidence level. This difference is hardly visible for time period FC1, and not at all visible for time period FC2.

3.2.2 Pipes and nodes affected by flow and exceeding water levels

Flooded nodes and pipe pressure are shown in Figure 4. For TC, floods are occurring mainly in two places, while, in FC3, floods have spread over a wider area and to other locations as well. The three circles show where problems will occur in the future time period FC3. Maximum storm water flow ratio (Q/Q_f) in the network has increased considerably between the two time periods. Values for A2 FC3 are similar.

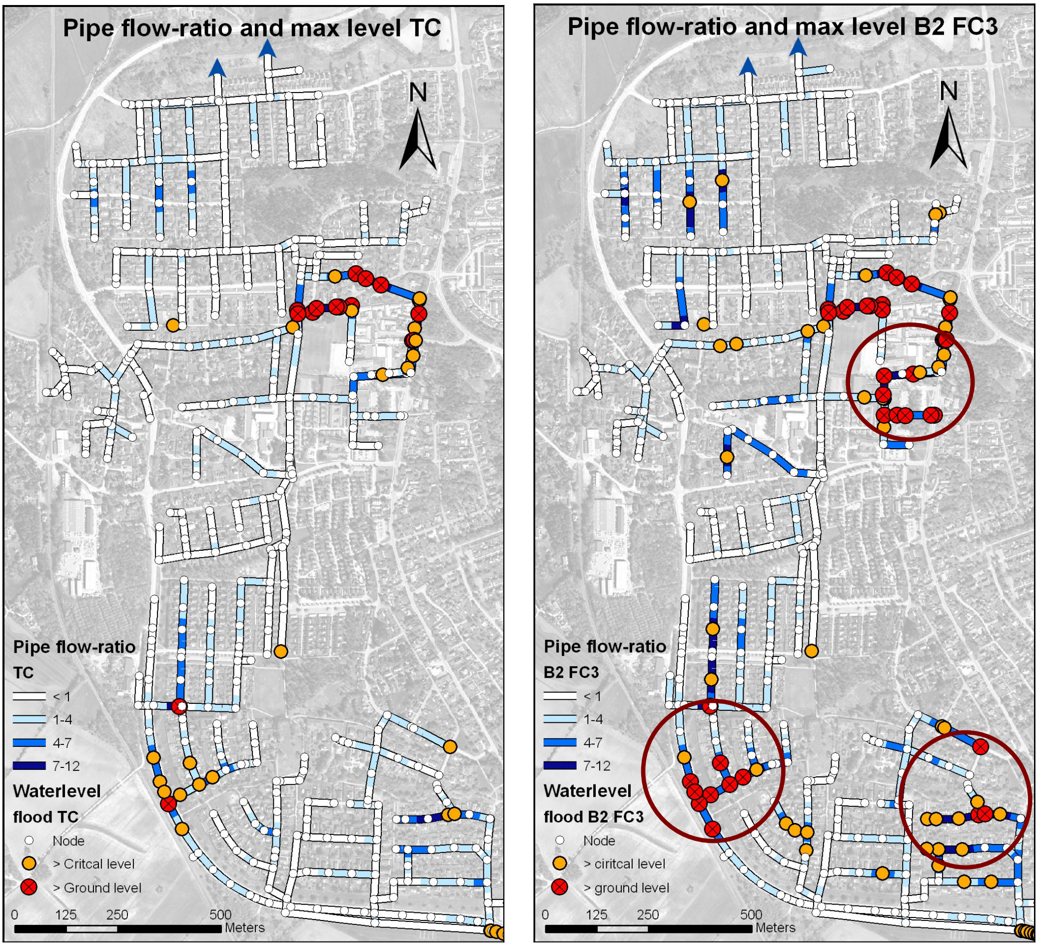

Figure 4. Left: Flooded nodes and nodes where critical level is reached for TC and in the complete system. Network shows water flow-ratio (Q/Q_f). Right: Flooded pipes and nodes, scenario B2, in future time period FC3. Network shows water flow-ratio (Q/Q_f).

The number of nodes flooded (water exceeding ground level) in today's climate increases a bit for future time periods (FC1, FC2, FC3) for both scenarios A2 and B2. The number of nodes where water is exceeding the critical level in the system (0,5m below ground level) is naturally higher at all time periods and increases also from today's climate to future time periods. Table 1 shows the number of nodes at each level and scenario.

Table 1. Number of nodes exceeding ground/critical level in the system, comparing differences between time periods TC, FC1, FC2, FC3.

		TC	FC1	FC2	FC3
A2	Ground level exceedings	7	9	11	16
	Critical level exceedings	58	65	69	81
B2	Ground level exceedings	7	11	12	16
	Critical level exceedings	58	66	70	83

3.2.3 Frequency

Figure 5 shows an increase in affected nodes in all intervals and especially in nodes where one to two floods occur. The left diagram shows actual flood events, and the diagram to the right describes the potential flooding events (critical-level exceeding), provided that there are even higher intensity rainfalls. Since the number of events is limited, only three intervals are given. The overall tendency is that future precipitation will increase the number of nodes flooded and also the flooding frequency. There are a few nodes involved in the flooding events for frequencies higher than nine, both today and for future time periods. Differences in scenario A2 and B2 are negligible, thus only A2 is presented here.

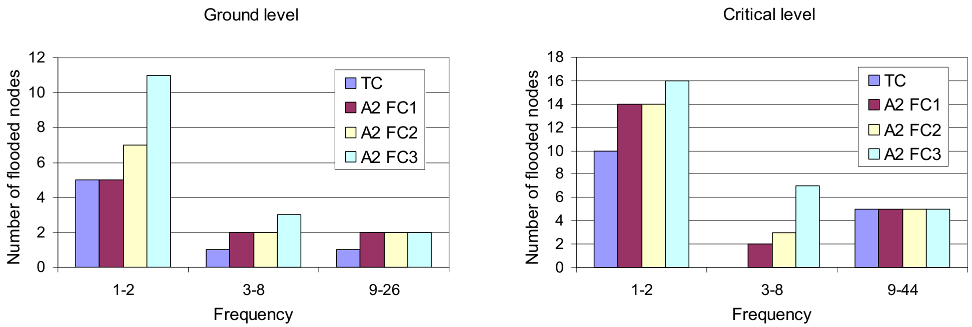

Figure 5. Frequency of “flooded” nodes, scenario A2. To the left: ground level exceeding, to the right: critical level exceeding (-0,5 m).

3.2.4 Duration

Figure 6 shows an increase in flood duration from today and in the future time periods. This measure is described from unique flood events, thus no consideration is given to the fact that the same node may be flooded several times. As for frequency, the left diagram shows duration of real flood events, while the right diagram presents an indication of the system’s capacity (critical level). Even though the number of events differs greatly between the diagrams, the tendency of increased duration is similar. The differences between the two scenarios are negligible, thus only A2 scenario is presented in the figure.

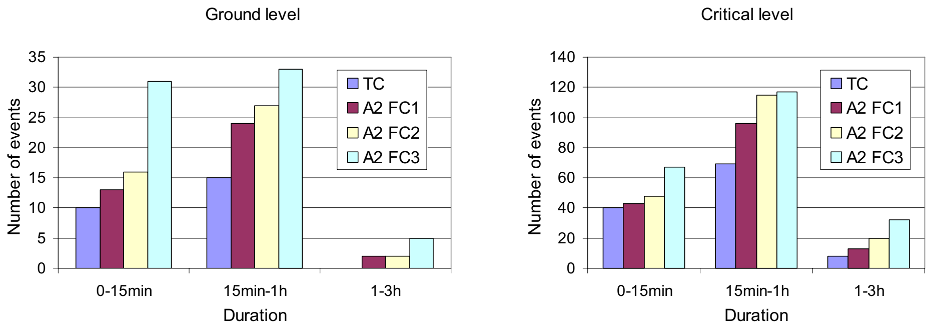

Figure 6. Number of flooding events for different durations, scenario A2. To the left: ground level exceeding, to the right: critical level exceeding (-0,5 m).

3.2.5 Maximum duration

The duration when water is exceeding ground level in the system is also measured as maximum duration. The node with the highest maximum duration in today's climate (43 min) will show a doubled duration for the time period representing distant future climate (FC3: 86 min for A2 and 83 min for B2). For the other time periods (FC1, FC2), the maximum durations are 63 min and 71 min respectively (for both scenarios A2 and B2). The greatest increase of duration from TC to FC3, for all the studied nodes, was from 15 min to 108 min/101 min (A2/B2). The analysis consists of 16 nodes, as they are the ones where flooding occurs in FC3. When the maximum duration of the two scenarios A2 and B2 is compared within the same time period (FC1:A2-FC1:B2, etc), there are no, or very few (FC3), significant statistical differences between the scenarios, at a confidence level of 95 %, using a t-test analysis.

4 Discussion

This paper shows that more urban flooding events are to be expected in the future, a conclusion that is also in line with the results from IPCC (2007), which point out that more heavy precipitation events will very likely occur in the 21st century. If this is the case, then there will be a great need to consider future plans to adapt the system, in order to cope with future conditions. But, is it possible to meet this development in an appropriate way? The rate of renewing may, however, serve as a buffer, lessening the consequences if future demands are gradually adapted as well Still, there is a need to investigate the future demands in order to make the right decisions. The characteristics of a whole system are indeed very complex, as every part of it is unique. When a new system is being designed, the rain return period must be considered. However, differences will still occur as the pipes themselves have certain fixed diameters. Thus, the capacity will be higher at the beginning of the pipe than at the end (downstream).

The number of flooding events in the urban drainage system will increase between today (TC) and the future time periods (FC1, FC2, FC3), for both scenario A2 and B2. As shown by the results, there are differences between the time periods and, as expected, the conditions regarding floods (the number of events, frequency and duration of floods) will also be worse in the distant future compared to the near future. According to Figure

4, flow-ratio in the system is increasing from TC to FC3, which will cause problems, even if the water does not exceed ground level. Pipes may leak and fill material may erode, which may undermine and cause damage to streets and houses. This will lead to economical consequences for both real estate and network owners.

The hydraulic parameters (maximum water levels in nodes, flooded pipes and nodes, exceeded critical levels in nodes, pipe fill, frequency, and duration) have been chosen in order to describe impacts due to climate change in urban drainage systems. The advantages of these parameters are their fast hydraulic response and their presenting of the system's capacity in a simple manner. This approach addresses hydraulic impacts directly and the parameters found in the literature that can be compared are peak discharge /flows (Waters et al., 2003) and the number of properties flooded (Ashley et al., 2005). Other parameters found in literature but not included in this paper are runoff volume (Waters et al, 2003), time to peak discharge (Waters et al, 2003), inflow to WWTP (Semadeni-Davies, 2004) and combined sewer overflow (Niemczynowicz, 1989; Semadeni-Davies et al, 2006).

The parameters describing flooding are a good indicator of urban drainage problems due to climate change, as they can point out areas where the capacity of the system is exceeded, both in pipes and in nodes (e.g. ground level or a predefined critical level below ground). Apart from describing the dynamics of a sewer system, the hydraulic parameters might also serve as input for economical calculations that describe potential losses for both network owners and property owners in a more detailed way. If the critical level (below ground level) is used as a parameter, the security level of the system will be estimated.

A scenario of the future involves a lot of uncertainties, and these should also be considered, if possible, when presenting data that have consequences for the future. However, uncertainties are not easily described or calculated, but may, on the other hand, be included as the basic data are produced from two future scenarios (A2, B2), which are both intermediate. The two scenarios make it possible to present the results as an interval. Still, future results may differ from these calculations, especially as the climate model data in general do not describe extreme events very well. These extreme events (e.g. rainfall during thunderstorms) may, in the future, cause the most damage.

Further research within this project contains analysis of the kinds of consequences that higher water levels, changed snowmelt patterns, increased maximum flow, and higher seasonal variations will have not only on the urban drainage system but also for other infrastructures.

5 Conclusions

The number of flooded nodes as well as the geographical distribution of the floods increases during the future time periods (FC1, FC2, FC3) for both scenarios A2 and B2.. The tendency is that future precipitation will increase both the flooding frequency and the duration of floods; therefore, the need to handle future situations in urban drainage systems and to have a well-planned strategy to cope with future conditions is evident.

In this study, three areas within the system will mainly be affected in the future: where resources should be allocated, if one takes into account secondary effects that the system might show downstream. For future considerations and for renewal plans, dividing the system into security levels/classes, where the critical level below ground will give earlier indications of capacity failure, might be preferable.

Finally, the results from this paper also indicate the need of climate model rainfall data dissagregation or transformation in both temporal and spatial resolution, in order to be appropriate for use in urban drainage model simulations.

6 Acknowledgements

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