DOCTORAL THESIS

Urban Stormwater Systems in Future Climates

Assessment and Management of Hydraulic Overloading

Karolina Berggren

LULEÅ UNIVERSITY OF TECHNOLOGY

Urban stormwater systems in future climates
- Assessment and management of hydraulic overloading

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Doctoral thesis

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/ *Karolina Berggren*, Luleå, May 2014

Abstract
Increasing global temperatures and tendencies of more frequent extreme weather events have been observed over the recent decades, and the continuation of this trend is predicted by future climate models. Such climatic changes impact on many human activities and hence the interest in, and focus on, climate change has increased rapidly in recent years. One of the fields strongly affected by ongoing climate change is urban water management and, in particular, the provision of urban drainage services. Modern urban drainage systems (UDSs) are designed to manage stormwater and convey residual runoff from urban areas to receiving waters, in order to fulfill such UDS primary functions as e.g., preserving local water balance; mitigating increases in runoff and the associated flood risks; and protecting water quality. There are also other drivers that influence the future urban runoff regime and the UDS performance, including urban planning, land-use changes (progressing urbanization), and implementation of sustainable stormwater management systems by such approaches as e.g., Best management practices (BMPs), Low impact development (LID), Water sensitive urban design (WSUD), and Green Infrastructure (GI).

This doctoral thesis focuses on urban rainfall and runoff processes, and runoff conveyance by separate storm sewer systems, and the changes in these processes caused by climate change, with the overall objective of investigating urban stormwater systems response and performance related to future climate changes, and particularly the future rainfall regime, by means of urban rainfall/runoff modelling. Furthermore, future influences on the runoff regime of urban green/pervious areas have also been studied. Specifically, the thesis has focused on future rainfall changes and hydraulic performance of the stormwater system, and the influential response parameters needed for evaluating the simulated impacts, with the overall aim of contributing new knowledge to this field.

The results included in the thesis are based on three published journal papers, one manuscript, and three conference papers. The research project started by addressing the needs for relevant UDS hydraulic response parameters (or indicators), which reflect both the capacity exceedance (when the UDS design fails) and indicate the safety margins in the system (e.g., locations with low or high capacities). The pipe flow rate and maximum water levels in the system exceeding a critical level, are examples of such parameters. Another issue addressed in this thesis is the difference in resolution (temporal and spatial) of the original climate model data (even if downscaled) compared to the requirements on rainfall input data in urban drainage modelling. Therefore, an existing statistical downscaling method (the delta change method, DCM) was refined by focusing on changes in rainfall intensities and seasonal rainfalls, and the refined DCM was recommended for use in UDS modelling.

The UDS performance in future climates, studied by modelling these systems, showed that a future change in rainfall poses significant impacts on the existing UDSs. Important aspects in addressing such impacts are, for example, the input rainfall data types (e.g. design storms, or observed rainfall), as well as the climate factors, and the methods used to produce such factors. Green/permeable areas within the urban catchments may, however, provide opportunities for adaptation of urban catchments

and UDS, by potentially increasing the infiltration of rainwater, instead of converting it into rapid runoff contributing high flows and flow volumes to the urban drainage systems. Influential factors in these processes include soil types, soil moisture content, groundwater levels and the rainfall input. While climate change with uplifted rainfalls tends to increase runoff contributions from all urban surfaces (impervious and green/pervious), strategic application of runoff controls in the form green infrastructure may counterbalance such increases, and even lead to reduced runoff inflows into the UDS.

Sammanfattning

De senaste årens observation av ökad global temperatur och tendens till fler extrema väderhändelser, i kombination med scenarier om fortsatta förändringar av klimatet, har ökat intresset för studier av dess effekter på samhället i stort och människors vardag. Ett område med tydlig koppling till denna problematik och med stor potential att påverka samhällets funktioner, är den kommunala dagvattenhanteringen, d.v.s. hantering av regn, snösmältning och ytavrinnande dagvatten i städer. Dagens dagvattensystem är uppbyggda under lång tid (olika delar med olika ålder, under olika utvecklingsfaser i staden). Systemen har som övergripande syfte att hantera och avleda dagvatten till recipienter, att bevara den lokala vattenbalansen, samt att minska risken för översvämningar och föroreningsspridning. I ett förändrat klimat, framför allt med fokus på förändringar av regn, påverkas dessa funktioner och kan leda till problem i urbana områden. Förutom klimatet, finns även andra faktorer som kan påverka avrinningssituationen, t ex urbanisering och förtätning, men också stadens planering och införandet av hållbara dagvattenlösningar, baserat på t ex ”grön infrastruktur”.

Det övergripande syftet med denna avhandling är att undersöka dagvattensystemens hydrauliska funktion relaterat till framtida klimatförändringar, och särskilt framtida regn, med hjälp av urbanhydrologisk modellering. Arbetet har därför delats in i fyra grupper: (1) utvärderingsparametrar för beskrivning av kapacitet och påverkan på befintliga dagvattensystem; (2) överföring av klimatmodellers information till urbanhydrologiska modeller (och små avrinningsområden); (3) bedömning av hydraulisk påverkan på dagvattensystem, beroende av olika typer av regn, och två olika metoder för att beskriva framtida förändring av regn; samt (4) gröna områdens inverkan på dagvattensystemets funktion och den urbana avrinningssituationen, i ett framtida klimat.

Resultaten i denna avhandling pekar på behov av relevanta utvärderingsparametrar som tydliggör kapacitetöverskridande (i systemet), samt kan visa på säkerhetsmarginalen i systemet (t.ex. områden med låg eller hög kapacitet). ”Pipe flow rate” (ledningsflöde), och maximala vattennivåer i systemet, är exempel på sådana. Avhandlingen tar också upp skillnader mellan upplösning (i tid och rum) av klimatmodelldata i sin ursprungsform i förhållande till behov vid urbanhydrologisk modellering, vilket lett till vidareutveckling av en befintlig metod (”delta change”). Detta har gjorts med fokus på nederbördens intensitet, och skillnader mellan årstider. En förändring av regn till en framtida ökad intensitet innebär större påfrestningar på dagvattensystemen.

Viktiga aspekter vid bedömning av effekterna vid modellering är vilken typ av regn (t.ex. ”designregn”, eller uppmätta regnserier), såväl som klimatfaktorer. De gröna/genomsläppliga områdena inom avrinningsområdet kan dock fungera som en resurs vid anpassning av städer, eftersom de har potential att öka andelen infiltration, i stället för avrinning till dagvattensystemen. Faktorer som studerats i denna avhandling och har stor inverkan på avrinningen, är jordart, markfuktighet, grundvattennivå, och regnets inverkan. Men även andra faktorer påverkar, t ex områdets karaktär i form av storlek, utformning, topografi, lutning, etc. Även om framtida klimatförändring med förändrade regn tenderar att öka avrinningen från alla urbana ytor (både hårdgjorda och gröna/genomsläppliga områden), så kan införandet av dagvattenlösningar baserat på grön infrastruktur (eller liknande) motverka dessa ökningar.

Table of Contents

List of papers

Paper I: Olsson, J., Berggren K., Olofsson M., Viklander M. (2009). Applying climate model precipitation scenarios for urban hydrological assessment: A case study in Kalmar City, Sweden, *Atmospheric Research*, 92(3), 364-375.

Paper II: Berggren, K., Olofsson, M., Viklander, M., Svensson, G., Gustafsson, A.-M. (2012). Hydraulic impacts on urban drainage systems due to changes in rainfall, caused by climate change, *Journal of Hydrologic Engineering*, ASCE, 17(1), 92-98.

Paper III: Berggren, K., Packman, J., Ashley, R., Viklander, M. (2013). Climate Changed Rainfalls for Urban Drainage Capacity Assessment, *Urban Water Journal,* (published online Nov 20, 2013, DOI:10.1080/1573062X.2013.851709)

Paper IV: Berggren, K., Gustafsson, A.-M., Marsalek, J., Ashley, R., Viklander, M., (2014). Climate change impact on soil moisture and runoff in urban green areas, (submitted manuscript)

Paper V: Berggren, K. (2008). Indicators for urban drainage systems – assessment of climate change impacts, *Conference Proceedings – 11th International Conference on Urban Drainage (11 ICUD), Edinburgh, Scotland, 31 August – 5 September 2008. 8p.* (oral presentation)

Paper VI: Moghadas, S., Berggren, K., Gustafsson, A.-M., Viklander, M. (2011). Regional and seasonal variation in future climate: is green roof one solution? *Conference Proceedings – 12th International Conference on Urban Drainage (12 ICUD): Porto Alegre, Brazil, 11-15 September, 2011. 8p.* (poster presentation)

Paper VII: Berggren, K., Moghadas, S., Gustafsson, A.-M., Ashley, R., Viklander, M., (2013). Sensitivity of urban stormwater systems to runoff from green/pervious areas in a changing climate, *Conference Proceedings – 8th International Conference on Planning & Technologies for Sustainable Urban Water Management NOVATECH 2013, 23-26 June, 2013, Lyon, France, 10p.* (poster presentation)

Contribution to papers

Karolina Berggren's contribution to the papers appended to this thesis covers different parts of the paper preparation: Idea, Literature review, Experimental design, Data collection, Data interpretation, and Writing (as shown in Table A).

Table A. Karolina Berggren's contribution to papers I-VII.

Paper	Idea	Exp. design	Data Collection	Data interpret.	Writing
I*	Shared responsibility	Shared responsibility	Participation	Participation	Participation
II**	Shared responsibility	Shared responsibility	Shared responsibility	Shared responsibility	Responsible
III	Responsible	Responsible	Responsible	Responsible	Responsible
IV	Responsible	Responsible	Responsible	Responsible	Responsible
V	Responsible	(Literature survey)	(Literature survey)	Responsible	Responsible
VI***	Minor participation	Minor participation	Minor participation	Minor participation	Minor participation
VII	Responsible	Responsible	Responsible	Responsible	Responsible

*Paper I: Collaboration with Dr.Jonas Olsson (Researcher at SMHI), and Shared responsibility with Mats Olofsson (former PhD-student colleague at LTU), **Paper II: Shared responsibility with Mats Olofsson (former PhD-student colleague at LTU), ***Paper VI: Minor participation, with main responsible Shahab Moghadas (PhD-student colleague at LTU).

Other publications by the author

Olsson, J., Olofsson, M., Berggren, K., Viklander, M. (2006). Adaptation of RCA3 climate model data for the specific needs of urban hydrology simulations, *Extreme Precipitation, Multisource Data Measurement and Uncertainty: Proceedings of the 7th International workshop on precipitation in urban areas. Molnar, P. (red.). Zürich: Institute of Environmental Engineering, ETH, Zürich, 144-148.* (poster presentation)

Berggren, K., Olofsson, M., Viklander, M., Svensson, G. (2007). Tools for Measuring Climate Change Impacts on Urban Drainage Systems, *Conference Proceedings – 6th International Conference on Planning & Technologies for Sustainable Urban Water Management NOVATECH 2013, 24-29 June, 2007, Lyon, France, 8p.* (oral presentation)

Berggren, K. (2007). *Urban Drainage and Climate Change – Impact Assessment,* Licentiate thesis, 2007:40, Luleå University of Technology, Luleå, Sweden

Berggren, K., Lans, A., Viklander, M., Ashley, R., (2012). Future changes affecting hydraulic capacity of urban storm water systems, *Conference proceedings of the 9th International Conference on Urban Drainage Modelling: 4-6 September, 2012. Belgrade, Serbia. 8p.* (oral presentation)

List of Abbreviations

AMC	Antecedent moisture conditions
Block	Design storm hyetograph: the block type
BL	Baseline scenario
BMPs	Best management practices (related to stormwater management)
CC	Climate change
CDS	Design storm hyetograph: the Chicago Design Storm type, after Kiefer and Chu (1957).
CF	Climate factor
CL	Critical level (related to HGLE in the sewer pipe system)
CMD	Climate model data, original output from climate models
CSO	Combined sewer overflow
DC	Delta change
DCM	Delta change method
DS	Design storm (rainfall)
ET	Evaporation/Evapotranspiration
FC	Future climate
GCM	Global circulation model
GI	Green infrastructure (related to stormwater quantity and quality management)
GSE	Ground surface elevation
GW	Ground water level/ground water table
HGLE	Hydraulic grade line elevation
IDF	Intensity-Duration-Frequency rainfall relationships
IH	Infiltration High, in Sensitivity analysis in paper VII
IL	Infiltration Low, in Sensitivity analysis in paper VII
IPCC	Intergovernmental Panel on Climate Change
2LW	2 Layer water balance method in MikeShe
LAI	Leaf area index
LID	Low impact development (related to stormwater management)
PH	Precipitation High, in Sensitivity analysis in paper VII
PRP	Performance response parameter
RCM	Regional climate model
RE	Richards equation (related to unsaturated soil water flow)
SA	Sensitivity analysis
SE	Single event rainfall
SMA	Safety margin approach
SUDS	Sustainable urban drainage systems (related to stormwater management)
SV-Di	St. Venant diffusive wave
SV-Dy	St. Venant dynamic wave
SWWA	Swedish water and wastewater association – Svenskt Vatten
T	Return period (rainfall)
TA	Time area method (based on Rational method)
TC	Todays climate
TS	Time series rainfall
UD	Urban drainage
UDS	Urban drainage systems
WL	Water level
WSUD	Water sensitive urban design, (related to stormwater management)

1 Introduction

Increasing global temperatures and frequencies of extreme weather events have been reported by the World Meteorological Organization (WMO 2013) for the last decade (2001-2010) and confirm the climate trends identified by the Intergovernmental Panel on Climate Change (IPCC 2013). Furthermore, the modelling of future climate scenarios indicates the continuation of these trends (IPCC 2013; WMO 2013), which result from increased global temperatures and higher atmospheric moisture content causing, among other effects, increased severity of extreme rainfall events (Trenberth 1999). Such climatic changes impact on many human activities and hence the interest in, and focus on, climate change has increased rapidly in recent years. One of the fields strongly affected by on-going climate change is urban water management and, in particular, the provision of urban drainage services (e.g., Semadeni-Davies 2003; Waters *et al.* 2003; Ashley *et al.* 2005; Denault *et al.* 2006; Willems *et al.* 2012 b).

Modern urban drainage systems (UDSs) are designed to manage stormwater and convey residual runoff from urban areas to receiving waters, in order to fulfill such UDS primary functions as preserving local water balance, including the groundwater regime and baseflow characteristics; mitigating increases in runoff and the associated flood risks; preventing harmful geomorphic changes; protecting water quality; preserving ecological functions; and, creating opportunities for beneficial uses of urban landscape and environment (mostly aesthetic amenities, recreation, and subpotable water supply) (Marsalek *et al.*, 2008).

Climatic changes, including higher intensities and depths of rainfall, will impact UDS performance, particularly with respect to flooding, and will directly influence the capacity of urban areas to cope with extreme events and flooding (e.g. Semadeni-Davies 2003; Waters *et al.* 2003; Ashley *et al.* 2005; Denault *et al.* 2006). There are also other drivers that influence the future urban runoff regime and the UDS performance, including urban planning, land-use changes (progressing urbanization) (e.g. Booth 1991; Semadeni-Davies *et al.* 2008a,b; Mott MacDonald 2011), implementation of sustainable stormwater management systems by such approaches as Best management practices (BMPs), Low impact development (LID), Sustainable Urban Drainage Systems (SUDS), Water sensitive urban design (WSUD), Green Infrastructure (GI), and sustainable operation and management of these systems (e.g. Gill *et al* 2007; Ellis 2013).

The doctoral thesis that follows focuses on urban rainfall and runoff processes, and runoff conveyance by separate storm sewer systems, and the changes in these processes caused by climate change.

The essential points of this scientific inquiry include identification of useful UDS response parameters describing hydraulic performance, further development of an existing method for statistical downscaling of climate model information for the use in UDS modelling, examination of the response of UDS to runoff from urban green areas exposed to future uplifted rainfall, and examination of the potential of a selected stormwater management measure (green roofs) for catchment adaptation to a future rainfall regime. These processes are graphically depicted in Figure 1.

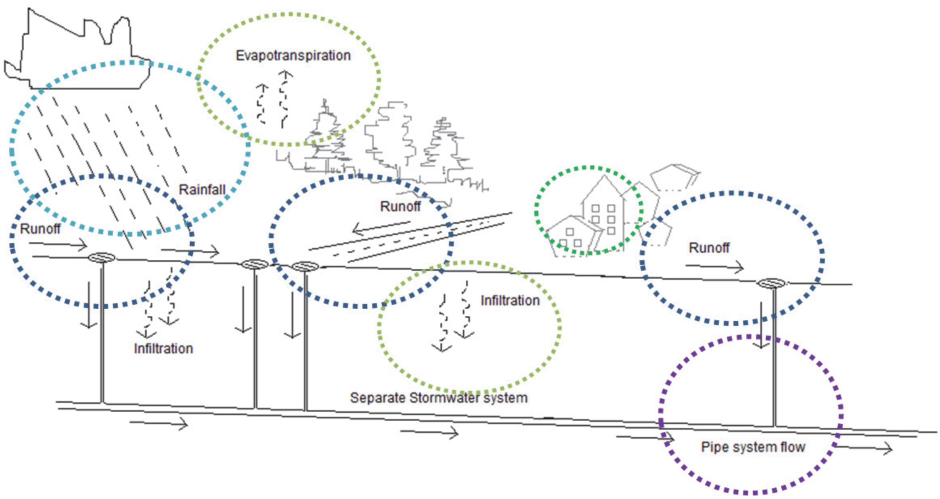

Figure 1. Schematics of the research area related to separate storm sewer systems, with main focus on rainfall (light blue) and urban runoff (dark blue) processes, including urban green areas (green), and sewer system performance (violet). Minor focus concerns hydrologic abstractions (infiltration and evapotranspiration) on green areas (green) and one selected adaptation method (green roof).

1.1 Thesis objectives and expected outcomes

The overall objective of this thesis is to investigate urban stormwater systems response and performance related to future climate changes, and particularly the future rainfall regime, by means of urban rainfall/runoff modelling. Furthermore, future influences on the regime of runoff from urban green areas have been also studied, as was an example of adaptation, typified here by green roofs.

The thesis has focused on future rainfall changes and hydraulic capacity/performance of the stormwater system, and the influential parameters needed for evaluating the simulated impacts, and the aim has been to contribute new knowledge to this field. To meet the thesis objectives, four research questions have been defined as presented below.

1.1.1 Research questions

1. What response parameters of UDS hydraulic and hydrological impacts due to climate change should be used, to describe adequately safety margins of a UDS and their changes in time?

2. How to process climate change rainfall from global and regional climate models to derive rainfall inputs to urban drainage models, with sufficient temporal and spatial resolutions?

3. How do different types of rainfall inputs, derived from downscaled climate change scenario data, influence the results of assessing climate change impacts on performance of UDSs by urban drainage modelling?

4. How do green urban areas influence future urban runoff and the associated urban drainage performance?

1.1.2 Expected thesis project outcomes

Answers to the research questions should provide the expected thesis project outcomes, which can be listed as:

- Recommendations of UDS performance response parameters supplementing the existing ones and describing better safety margins in UDS, which become hydraulically overloaded because of climate change

- Recommendations for the use of rainfall inputs associated with climate change information, for modelling the performance of existing UDS in a future climate,

- New knowledge on potential changes in runoff from urban green areas in the future rainfall/runoff regime, and

- A preliminary assessment of one climate change adaptation measure, green roofs.

1.2 Thesis outline

First section, the *Introduction*, introduces the thesis topic (climate change and urban drainage), presents thesis objectives, followed by a list of research questions, and explains the role of the appended papers in addressing the thesis objectives and research questions. Next section, *Background*, represents a literature review on the four main thesis research areas and their interfaces: Urban drainage (UD), Rainfall, Climate change and UD models. In this section, key aspects relevant to the thesis research field, are summarized. The section on *Methods* describes the tools and procedures used in conducting research and focuses on urban drainage modelling; additional technical details are given in the appended papers.

Next section is titled *Results and Discussion* and summarizes relevant findings from the appended papers and new analysis, and provides answers to the research questions listed earlier. The section is organized around the research questions. The discussion part elaborates on limitations of and uncertainties in research results, and discusses them in the context of research published in this field. The following section presents *Conclusions* related to the thesis findings and to the research questions. Finally, *References* are listed, followed by the *appended candidate's papers*.

1.3 Organization of papers

The papers included in this PhD-thesis are related to the urban drainage rainfall-runoff processes as outlined in Figure 2, with papers numbered according to the List of papers (on page IX). Paper linkages in terms of flow of data and results, and their use in subsequent papers, are shown in Figure 3. More specific information about the paper linkages can be found in the Methods section.

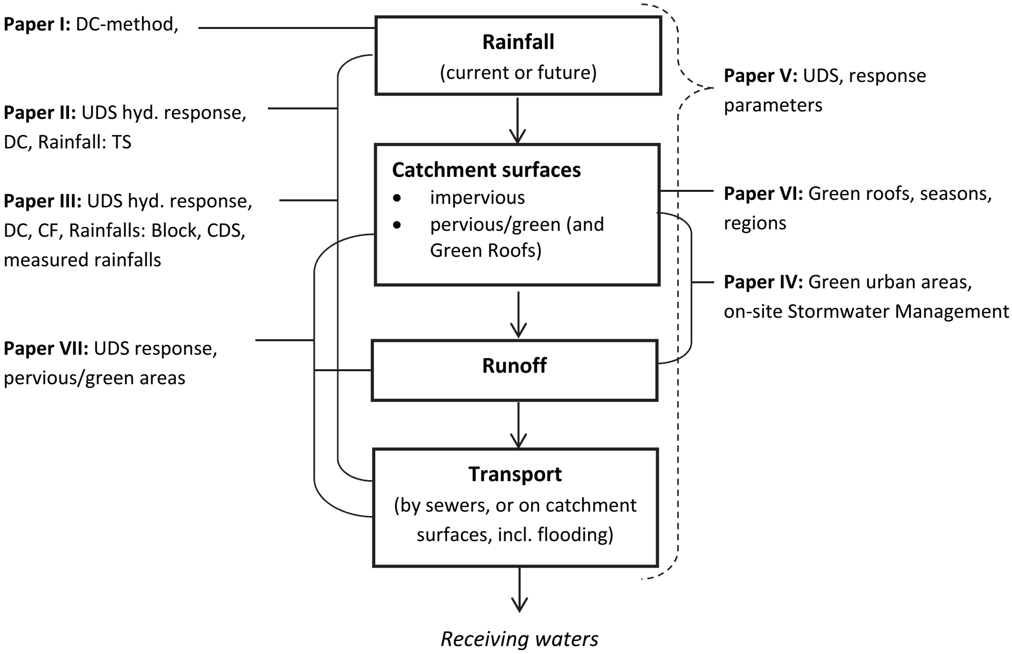

Figure 2. Organization of papers (DC – Delta Change, UDS – Urban drainage systems, TS – time series rainfalls).

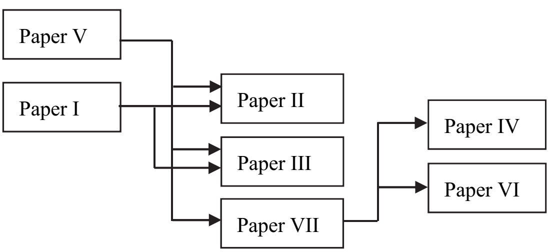

Figure 3. A flowchart indicating linkages and flow of information among the thesis papers.

2 Background

This thesis addresses the performance of urban drainage systems in a changing climate and the assessment of hydraulic safety margins in the system and the associated urban area. The most important aspect of such performance is the management of risk of flooding (including water ponding), which is examined for catchments served by separate storm sewers. Thus, the Background section reviews information about (1) Urban drainage (rainfall/runoff processes, design standards and regulations); (2) Climate change, and (3) Modelling tools for assessing hydraulic-hydrologic influences of climate change on UDSs.

2.1 Urban drainage

Urban drainage provides a number of benefits to urban dwellers, including reduced risk of flooding or inconvenience due to water ponding, alleviation of health hazards, improved aesthetics of urban areas, and even subpotable water supply. With reference to flooding, urban drainage systems are often classified into two types: minor and major drainage systems (e.g. Walesh 1989; Marsalek *et al.* 2008). Minor systems comprise street gutters, storm sewers, swales, drainage surfaces and runoff control facilities and are typically designed to convey runoff (also called stormwater) from storms with 2-10 year return periods (Marsalek *et al.*, 2008). Design of such systems is described in design standards (e.g. European Standard: EN752, EU (2008)) and national recommendations (e.g. in Sweden by Swedish Water and Wastewater Association, SWWA (2004)). Flows in excess of the minor system design capacity are conveyed by major drainage, comprising streets, swales, water impoundments, streams and rivers. Major drainage is designed to convey runoff (flood flows) from infrequent storms with return periods ranging from 50 to 100 years (Marsalek *et al.*, 2008).

Two significant trends have occurred in urban drainage in many countries, including Sweden, during the last 65 years: (a) Preferential use of separate sewer systems (Bäckman 1985), even though combined systems can still be found in older parts of cities and may represent about 15% of the total length of sewers in Sweden (Mikkelsen *et al.* 2001), (note that in Denmark this proportion is greater, 45%, and even more combined systems is found in UK, France and Germany (70%) (Butler and Davies 2004)), and (b) more recently, changes in the urban surface drainage practice by focusing on stormwater quantity and quality management by landscape-based approaches emphasizing the role of green (pervious) areas and nature-mimicking flow channels. These features are included in such design concepts as Best Management Practices (BMPs), Sustainable Urban Drainage Systems (SUDs), Low Impact Development (LID) measures, and Green Infrastructure (GI) (e.g. Ellis 2013). These advanced approaches increase sustainability and robustness of drainage systems in coping with future changes (e.g. Gersonious *et al.* 2012).

Notwithstanding the importance of urban stormwater quality and its impacts on receiving waters (US EPA, 1983; Marsalek *et al.* 2008), the topic of this thesis addresses minor stormwater drainage and its ability to convey drainage flows encountered in the current and future climates. Other elements of UDSs may be discussed herein briefly, with respect to their interactions with drainage conveyance systems, and include stormwater management facilities.

For assessing urban runoff and the associated hydraulic performance of an UDS in runoff conveyance, the important elements can be listed as follows:

- **Catchment:** Physiographic catchment characteristics – including the size, slope, shape, and imperviousness of the drainage area; drainage patterns (determining the time of concentration for the whole area and subareas within the urban catchment and the most appropriate rainfall durations to be used); and, the presence of stormwater management facilities (e.g., Marsalek *et al.* 2008);

- **Regulations and Standards:** these documents specify the level of drainage service (protection) to be provided, which in turn defines the return period of the design rainfall or actual flood event. Such information is given in e.g. European Standard (EU 2008), and national recommendations (e.g. in Sweden, SWWA 2004);

- **Rainfall:** described by rainfall depths/intensities with adequate resolution in time and space - short time intervals and multiple rainfall records are recommended (e.g. Schilling 1991); and,

- **Modelling tools and set up:** Suitable runoff computation procedures, which currently may be as sophisticated as 1D/1D or 1D/2D hydrological models (e.g., Leandro *et al.* 2009).

2.1.1 Runoff processes

Rainwater falling over urban areas generates surface runoff, depending on both rainfall characteristics and the properties of the catchment surface. Focusing on rainfall, early research on design storms pointed out the importance of rainfall characteristics in computations of runoff, including: "(a) design return period; (b) storm duration; (c) intensity-duration-frequency (IDF) relations, representing a summary of historical rainfall data, with some extrapolation for longer return periods; (d) temporal distribution (design hyetograph); (e) areal reduction factor; and, an associated factor referring to the catchment "wetness" state, (f) antecedent moisture conditions (AMCs)" (Marsalek and Watt 1984; Watt and Marsalek 2013). The authors noted that much research was done concerning (a)-(d), and relatively little concerning the areal reduction factor and antecedent moisture conditions. Little information is available on AMCs, especially with supporting runoff flow data, and consequently, AMCs are either assumed, or determined from empirical formulas or soil moisture models (e.g. Nishat 2010), but without field validations. In the former case, AMCs are typically assumed as dry or wet (e.g. Deletic 2001; Villarreal *et al.* 2004), where the latter assumption contributes to maximum runoff volumes and peaks for a given storm (e.g. Packman and Kidd 1980; Arnell 1982; Marsalek and Watt 1984).

Urban areas comprise both impervious and pervious surfaces (examples are shown in Figure 4), which contribute in different ways to the total surface runoff, because of differences in their hydrological abstractions, surface roughness and water storage. Impervious areas comprise unconnected and directly-connected impervious sub-areas, which are characterized by low hydrological abstractions and surface roughness, and in the latter case, represent major sources of rapid runoff with high peak flows (in Figure 5, the Post-Development runoff hydrograph). Therefore, the early assessments of UDS capacities have focused largely on runoff from (directly-connected) impervious areas.

Contrarily, pervious areas produce less runoff, and attenuated and delayed peak flows (e.g. Chow *et al.* 1988; Marsalek *et al.* 2008), as shown schematically in Figure 5 (Pre-Development runoff hydrograph). Surface runoff then enters storm sewers through inlets, but if the sewer system capacity is insufficient, excess stormwater remains on the catchment surface and contributes to surface flooding and inundation.

Figure 4. Impervious urban area (to the left, photo by K. Berggren) and green/pervious urban residential area (to the right, photo from Kalmar by S. Ahlman, used with permission).

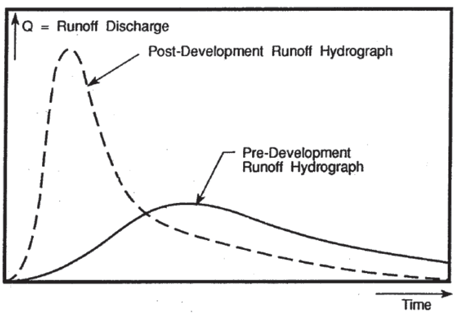

Figure 5. Catchment runoff hydrographs: Before urbanization (Pre-Development, a rural area with low imperviousness), and after urbanization (Post-Development, an urban area with high imperviousness) (Adapted from Marsalek *et al.* 1992, used with permission).

The rates of conversion of rainwater into runoff from urban areas without stormwater controls can be high, in the range from 70-80% for densely developed areas and up to 90% for roofs (calculated by the Rational method and the runoff coefficients suggested in SWWA (2004)). Runoff from suburban areas with lower density of development, may contribute just about 25-50% of total catchment runoff, and even less (10-20%) in the case of green/pervious areas (SWWA 2004). Consequently, diversion of runoff from impervious areas onto pervious areas is one of the most common runoff management measures.

Besides peak flows, annual water balance is also of interest. Arnold and Gibbons (1996) pointed out that the annual water balance is affected by the catchment imperviousness; e.g. runoff from residential areas with 10-20% imperviousness represents about 20% of the annual balance and this percentage further increases with increasing imperviousness (Table 1). Data in Table 1 show that evapotranspiration (ET) is not much affected by increasing imperviousness; ET is a relatively slow process, which is further affected by water availability. Examination of water balance during short rainfall events, which are typical for UDS design and capacity assessment, presented later in the Results section, will show that ET plays relatively minor role in water balances for individual events; however, such balances are strongly affected by rapid runoff and relatively fast infiltration processes. On a longer time basis, the infiltrated water will contribute to ET, and will influence the soil moisture conditions as well as groundwater levels (Chow *et al.* 1988).

Table 1. Annual water balance associated with different degrees of urbanization (after Arnold and Gibbons 1996).

Urbanization	**Runoff (%)**	**Infiltration (%)** *(deep and shallow)*	**Evapotranspiration - Evaporation (%)**
Natural ground cover	10	50	40
10-20% impervious	20	42	38
35-50% impervious	30	35	35
75-100% impervious	55	15	30

The data in Table 1 do not reflect site specific characteristics of urban areas, such as the soil type, the depth of the groundwater table, arrangements of green sub-areas (both horizontally and vertically) and their distribution in the urban landscape, as well as the characteristics of the impervious areas, catchment slope, and the UDS layout and capacity.

2.1.2 Design of urban drainage systems (UDSs)

UDSs should, irrespective of their age causing the system deterioration or needs for modifications, comply with the current design standards (e.g. European standard: EN752, (EU 2008)). However, depending on the catchment area and land use planning, the design criteria for individual UDSs can somewhat vary. According to the European standard (EU 2008), the design capacity of an UDS should be such as to convey floods with return periods ranging from 1 in 10 to 1 in 50 years, depending on the characteristics of the area (Table 2).

The prescribed level of service corresponds to the character of the urban area under consideration (e.g. rural, urban residential, downtown, etc.) and is regulated by the national legislation. In Sweden, on the other hand, the national recommendations do not classify the different urban areas in the same way as in the EU standard, nor recommend UDS design return periods higher than 1 in 10 years (SWWA 2004). For runoff computations in Sweden, the national recommendations of SWWA (2004) stipulate using the design storm, rather than the design flood, and the conveyance of the resulting runoff by sewer pipes flowing full (i.e., open-channel flow). This approach does not address explicitly the need to keep the hydraulic grade line below the basement or ground surface elevations, as done in the case of flooding analysis. However, new Swedish recommendations are to be published in 2014. An important fact should also be kept in mind - the UDS cannot be designed with a zero risk of flooding, contrarily to common expectations of urban dwellers. Furthermore, there are also differences between the design performance and the actual performance of UDSs.

Table 2. EU recommended design frequencies for use with complex design methods (EU 2008). Note that these recommendations somewhat differ from the current Swedish national recommendations (SWWA 2004).

Location	**Design flood frequency** Return period (1 in "n" years)	**Design flood frequency** Probability of exceedance in any 1 year
Rural areas	1 in 10	10 %
Residential areas	1 in 20	5 %
City centres/industrial/commercial	1 in 30	3 %
Underground railways/underpasses	1 in 50	2 %

The European standard EN 752 (EU 2008) and the associated national recommendations (e.g., in Sweden, SWWA 2004; 2011a;b) provide an important framework for designing new UDSs or evaluating the performance of existing UDSs. However, these recommendations do not always provide clear guidance for analyzing the existing UDSs with respect to: (1) types of rainfall data to use (time series, single event, design rainfall, synthetic rainfall, measured rainfall); (2) accounting for climate change (climate model data, global or regional models, scenarios, methods of downscaling or other uplift factor techniques); (3) the level of detail needed to adequately model the UDS; and, (4) simultaneous consideration of climate, catchment, and UDS changes in drainage management (e.g., other climate parameter changes besides rainfall, population and urban area changes, and changes of the UDS). Under such circumstances, the drainage standard is subject to various interpretations, which may increase design uncertainties.

In Sweden, and many other countries, the urban drainage design has since long focused mainly on the Minor system design (i.e., sewer pipe system), with less focus on the combined interactions between Minor and Major drainage systems (e.g. Ashley *et al.* 2007; Fratini *et al.* 2012). There are, however, trends to move away from focusing just on urban piped sewer system design and performance, towards a more holistic approach including the management of surface runoff processes (including the Major drainage system) and the decision making related to this approach (e.g. Ashley *et al.* 2007; Geldof and Kluck 2008).

The ideas related to the management of these interactions were presented by Geldof and Kluck (2008) in the "Three Points Approach" (3PA), which was further refined by Fratini *et al.* (2012). The 3PA focuses on management for different types of rainfalls: (1) technical optimization, dealing with standards and guidelines for urban drainage systems (design storm events); (2) spatial planning, making the urban area more resilient to future changing conditions (extreme rainfall events); and (3) day-to-day values, enhancing awareness, acceptance and participation among stakeholders (smaller rainfall events).

Further refinement of the 3PA in relation to the same ideas was also suggested in a publication from CIRIA (2014) (also Digman *et al.* 2014), introducing yet another domain in "the 4 domains approach". This approach grouped the domains in: (1) every day rainfall; (2) design rainfall; (3) exceedance rainfall (i.e. exceeding marginally the design rainfalls); and (4) extreme rainfall. The new domain focusing on the "exceedance" of design events (domain 3), highlighted the management of flooding with relatively minor adjustments to the local landscape, rather than strategic risk management of extreme events for complex major drainage problems and urban area interactions.

Another example of methods, which combine underground and above ground flooding and urban drainage system performance, is the "Mainstreaming Approach", focusing on "tipping-points" in both surface runoff transport and below the surface transport in UDS, adaptation measures related to future changes in the urban area (spatial planning) and climate change (Gersonious *et al.* 2012).

Overall, the growing interest in sustainable urban drainage solutions focusing on green/pervious urban areas (such as GI, SUDS, BMPs) enhances the need for a holistic approach, taking the whole (urban) water cycle into account in spatial planning as well as in urban drainage design and development. Also the modelling of urban drainage system performance has since long focused mainly on the piped sewer system performance (in 1D models), but more and more, it focuses on the urban area flooding as well, and on interactions between the Minor and Major drainage systems. For that purpose, the use of combined models (1D/1D or 1D/2D) was recommended (e.g. Leandro *et al.* 2009). Additionally, with more focus on urban green/pervious areas, the above-ground (surface processes) models also need to include the unsaturated and saturated zone processes (in 1D/3D models or 3D models) (e.g. used by Roldin *et al.* 2013).

Finally, it should be acknowledged, that even though the discussion herein focuses on flooding, there are also many other regulations governing UDSs, including the EU Water Framework Directive (EU 2000) (addressing the quality of stormwater impacting on large river catchments), EU Flood Directive (EU 2007), as well as in the Swedish context, Environmental Code (SFS 1998), Planning and Building Act (SFS 2010), and Water services Act (SFS 2006). These regulations cover different aspects of urban drainage and, together with the municipal stormwater policies, should promote better, more sustainable urban water management.

2.2 Rainfall

Depending on the study purpose, rainfall time series or single events, often applied as design storms derived from IDF curves, can be used as rainfall inputs. Swedish national guidelines (SWWA 2011a) recommend for the assessment of hydraulic performance of existing systems the use of a block-rainfall design storm, and for designing new systems the CDS rainfall, which is analogous to the Chicago Design Storm (CDS) (Keifer and Chu 1957). Such design storms are commonly used, especially when the available computing capacity is a limiting factor. Examples of block rainfalls of different durations and a CDS rainfall hyetograph are shown in Figure 6.

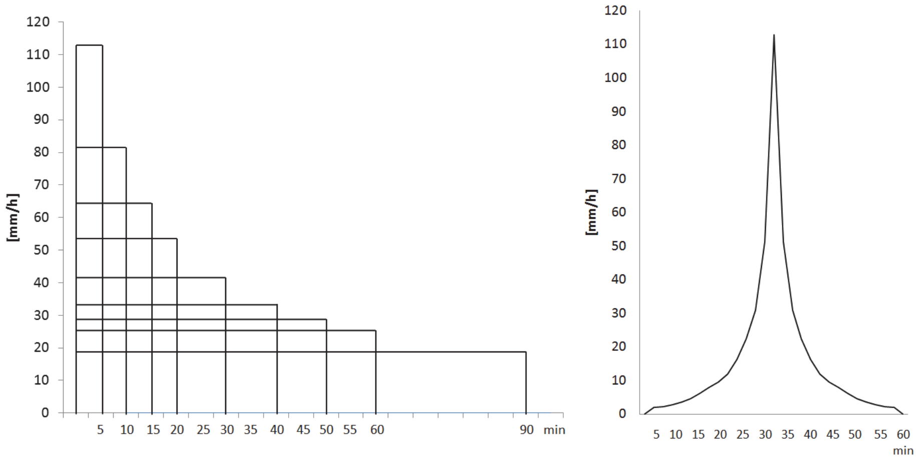

Figure 6. Ten-year design rainfalls: Block rainfall (5 – 90 min durations) (left) and CDS rainfall (right). The maximum 5-min rainfall intensity = 113 mm/h (rainfall intensities from Dahlström (2010)).

However, one limitation of using design storms is the choice of initial soil moisture conditions (Nishat *et al.* 2010; Camici *et al.* 2011). Continuous simulation using a rainfall time series accounts better for the AMCs and their effect on simulated runoff, provided that the runoff model used simulates hydrological processes on green areas with variable soil moisture conditions. Therefore, a local rainfall record of high resolution generally complements the results obtained with design rainfall. However, the lack of local rainfall data can be a problem in Sweden as the high resolution rain gauge network is not very dense.

IDFs are generally available in Sweden (Dahlström 2010) and their use is recommended by SWWA (2011a). It is worthwhile to note that the most recent assessment of rainfall records (Dahlström 2010) did not show statistically significant regional differences, which had been noted earlier (Dahlström 1979). Such differences may influence the evaluation of performance of existing UDSs as well as the design of new systems. For example in the Kalmar area, in south-east Sweden, the design intensity of a 10-year rainfall is 12-20% (depending on the duration) higher in the new recommendations compared to the older ones.

As the rainfall is the most important stormwater and runoff generating factor, it is important to understand its character. With an "engineering approach" related to the design of urban drainage systems and infrastructure, rainfall information is often used in a very simplified way (e.g. using design storms of Block or CDS type). However, as the future climate changes and more focus is placed on examining urban area flooding, and its interactions with UDS (e.g. Ashley *et al.* 2007; Fratini *et al.* 2012; Gersonious *et al.* 2012), these simplifications may need to be re-examined. This need will also increase with a further focus on implementation of more effective use of urban green/pervious areas in runoff control (related to water balance and runoff) (e.g., Ellis *et al.* 2013).

Characteristics of rainfall data (e.g., the type of rain gauges, locations, instrument density and temporal resolution) may also impose limits on the use of such data in modelling. Two characteristics that are commonly considered as essential in design and modelling of UDS: the temporal and spatial resolutions. Berndtsson and Niemczynowicz (1988) summarized the differences in temporal and spatial scales of rainfall data needed in addressing such hydrological problems as climate change (a century, large areas > 10,000 km^2) and urban drainage (minutes to hours, for catchments of sizes ranging from 10 to 100 km^2). Similar description was recently also presented by Willems *et al.* (2012b), pointing out the need for both temporal and spatial downscaling of climate model data required for urban hydrological impact studies.

For smaller urban catchments, the temporal resolution requirement was described by Schilling (1991) as low as 1 minute. Zhou and Schilling (1996) further reported that if the recording interval of rainfall data is too large, short-duration peak rainfall intensities are filtered out and, as a consequence, the modelled peak flow rates and volumes (determined for CSO overflow volumes) may be underestimated. They demonstrated such underestimation for two tested resolutions of 5 and 10 minutes. Similar results were also reported by others (e.g., Berne *et al.* 2004; Aronica *et al.* 2005; Schellart *et al.* 2012) and further extended by emphasizing the importance of high spatial resolution as well (Berne *et al.* 2004; Schellart *et al.* 2012). Requirements on spatial resolution then increased interest in the potential use of radar measured rainfall (e.g. Einfalt *et al.* 2004) in urban drainage modelling applications (Schellart *et al.* 2012), although further development of knowledge in this field is needed (Schellart *et al.* 2012; Nielsen *et al.* 2014). Radar rainfall data and climate model data output information both have a spatial character, which is different when compared to the point measurement of rainfall by rain gauges. In the latter case, the rainfall distribution in space may be obtained by employing a network of rain gauges. Also, moving storms exert influence on runoff modelling results, as reported e.g., by Niemczynowicz (1991), and such an influence may be accounted for by using radar rainfall.

Contrary to conventional assumptions in frequency analysis (Chow 1964), the rainfall statistics are not stationary over time, because of natural variability and climate change. Rauch and De Toffol (2006), for example, analysed six data series of 19-55 years in length from four countries and found no consistent trend of increasing severity of extreme rainfall events, whereas results from Denmark showed a general increase of rainfall intensities, with regional variability and a tendency of larger extreme events in the eastern part of the country (Madsen *et al.* 2009). Rana (2013) found an increasing number of extreme events of shorter return periods in southern Sweden, but not for the events with longer return periods. In analyses based on historical rainfall records, there are often problems caused by short records and low temporal resolutions. Thus, for rainfalls of short durations (as typically used in UDS design and performance analysis) the records are often too short to detect trends of change. The uncertainty also increases when extrapolating trends into the future, as discussed in the next section.

2.3 Climate changes

During the last decade the interest in climate change issues has rapidly increased, as a consequence of increased global mean temperatures and higher occurrences of extreme weather events (IPCC 2013). These increases have become more pronounced during the last decade (2001-2010), compared to the earlier records kept since 1850 (WMO 2013). Increasing temperatures also change the intensity of the hydrological cycle processes, as extreme weather and intense rainfall events are more likely to occur with higher temperatures in the atmosphere. In the future, further increases of temperatures are expected (IPCC 2013), which will impact on, for example, precipitation patterns, snow cover, sea levels, and extreme weather events. A summary of the IPCC findings regarding these phenomena is listed in Table 3, both for observed changes and the changes expected in the future, with focus on the northern hemisphere. In Sweden, all climate model data sets generally indicate wetter winters throughout the country, but drier summers in the south and wetter summers in the north (e.g. as described in SOU 2007).

Future climate projections are provided by global circulation models (GCMs), for future scenarios. In the most recent IPCC assessment report (IPCC 2013), the future scenarios are described as "Representative concentration pathways" (RCPs) (Moss *et al.* 2010), which are developed based on another method compared to the earlier emission scenarios (SRES: e.g. A1, B1, A2, B2, A1B) described by Nakicenovic *et al.* (2000). RCPs are focusing on the radiative forcing described by different future developments and named, e.g., RCP8.5 and RCP6.0 (Moss *et al.* 2010). The main driving forces for the development of SRES scenarios were population, economic and social development, energy and technology, agriculture and land-use emissions, and the related policies, and a total of 40 scenarios were divided in subgroups, e.g. A2, B2 (Nakicenovic *et al.*, 2000).

In the early research on climate change, the most commonly used scenarios were A2, B2, A1B, but currently, the RCP based scenarios are recommended. Additionally, it is recommended to use an ensemble of multiple climate projections to obtain some appreciation of projection uncertainties (e.g. Willems *et al.* 2012a;b).

Table 3. Summary of climatic changes that have been observed and those likely to occur in the 21st century (IPCC 2013), with focus on the parameters potentially impacting on UDSs, for various regions of Europe and North America.

Climate parameters		Climate changes, observed and future (modelled)
Temperature		The observed global average temperature has risen by 0.85°C ± 0.20°C over the years 1880-2012 (IPCC 2013). It is very likely that the warming will continue in the 21st century, although the warming is not evenly distributed in space, e.g. warming of the northern hemisphere is likely to be above the global average (IPCC 2013).
Precipitation	Amount	The changes in precipitation amounts differ from area to area; in general, dry areas will become drier (e.g. Mediterranean) and currently wet areas will become wetter (e.g. Northern Europe) (IPCC 2013).
	Intensity	In general, the intensity is likely to increase (IPCC 2013), as the hydrological cycle intensifies due to higher temperatures and higher atmospheric moisture content (Trenberth 1999).
	Frequency	Rainfall events regarded as extreme today are likely to occur more frequently in the future (Special report IPCC (2012), and IPCC (2013)), thus their statistical return period will also change (IPCC 2012).
	Snow	In general, the duration of snow season and snow depths are likely to decrease, with more rainfall instead of snow occurring because of higher temperatures.
Sea level		The observed global average sea level has increased by 0.19 m ± 0.02 m during the years 1901-2010, and will continue to rise in the 21st century (IPCC 2013). Thermal expansion of the ocean and loss of mass from glaciers and ice caps has contributed to the sea level rise (IPCC 2013).
Extreme weather events		Increases in the number of heat waves and the regions affected by droughts, as well as tendencies of increased numbers of heavy precipitation events, have been observed (IPCC 2013) and are likely to increase in the future, due to increased global temperatures (IPCC 2013; Trenberth 1999). Changes in storms (frequency, intensity, etc.) and small-scale severe weather phenomena are in general more difficult to be discerned in climate model results, in comparison to average changes over larger geographical areas (IPCC 2013).

Among the climate change parameters in Table 3, the following ones can be identified as relevant for the flow conveyance performance of UDSs:

- **Inputs:** Precipitation - rainfall and snow (represent UDS inputs).
- **Catchment:** Changes in catchment moisture conditions (affecting runoff generation and other runoff processes) caused by changes in temperature/evapotranspiration, in combination with changing rainfalls (represent UDS initial conditions with respect to runoff generation).
- **Boundaries:** Water levels at outlets (sea/lake/river) to receiving waters and groundwater levels, which form UDS boundary conditions with respect to flow routing.

With respect to catchments, other changes (not related to climate) are also possible in the future, e.g. progressing urban development (increasing imperviousness and the urban area growth), and adaptation actions. The UDS boundaries can also change, e.g. by regulation of water levels in rivers and lakes.

It should be also noted that already the current climate displays great variability between seasons, which is also relevant to the UDS performance over the course of the year. Normally, rainfall intensities for minor drainage design (e.g. sewer pipes) occur during summer (convective) rainfalls (e.g. SWWA 2004; Dahlström 2010), hence future seasonal changes in the climate may also influence the UDS performance.

2.4 Modelling UDS performance in a changing climate

2.4.1 Modelling UDSs

Hydraulic performance of UDSs, and water ponding on the catchment surface, can be simulated by advanced urban rainfall/runoff models. Over the years, many such models were published in the literature, but currently, vast majority of rainfall/runoff modelling worldwide is accomplished by three leading modelling packages, listed alphabetically as InfoWorks (Innovyze 2014), Mike Urban-Mouse (DHI 2011), and the US Environmental Protection Agency SWMM (Storm Water Management Model) (Rossman 2009). These leading models are robust and offer numerous advanced features, have been extensively tested, verified and continually supported and refined, and generally assessed as capable of simulating the generation and transport of urban runoff, for broadly varying conditions, with a high level of certainty (Zoppou 2001). Thus, these models represent logical choices of tools for testing the hydraulic conveyance performance of UDSs.

The process of modelling urban drainage comprising the catchment and UDS is schematically displayed in Figure 7 and includes the core element representing the actual model, with set up parameters, which is fed with input data and parameters, and produces output data and response parameters (Figure 7).

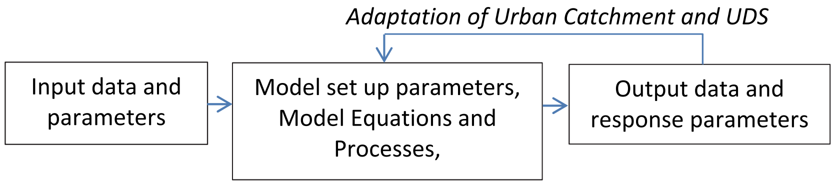

Figure 7. Conceptual description of modelling UDS.

When working with models, it is important to be aware of their limitations, including the completeness of processes incorporated in the model and the underlying assumptions (Beven 2001). Model performance can be improved by calibration, provided that measurements of rainfall and runoff flows are available at various points in the catchment. Ideally, the rainfall measurements should represent similar intensities as those to which the calibrated model is applied, but such data are rarely available. More often, the model is calibrated for lower intensity events and used to simulate runoff for higher intensities, which introduces uncertainties into simulation results and such uncertainties need to be considered in interpretation of simulation results.

For assessing UDS hydraulic performance in a future climate resulting in hydraulic overloading and exceedance of the system capacity, it is required to use a model with a runoff generation module and runoff routing simulating surcharged (pressurized) flows. Runoff generation modules compute rainfall excess by subtracting rainfall abstractions from the rainfall depth, with the most important abstractions in urban catchments being depression storage, infiltration on pervious surfaces, and evapotranspiration (Chow *et al.* 1988).

Rainfall excess forms overland flow whose hydrograph is simulated using such concepts as the time-area method, unit hydrograph, reservoir models, or kinematic wave (Butler and Davis 2004). Overland flow hydrographs (also called inlet hydrographs) enter sewers or drainage channels, and are synthesized and routed through the conveyance system. In these computations, storm sewer / channel flow processes are assumed to be one dimensional (1D), whereas surface overland flow is either simplified as a 1D process (i.e., modelled as an open-channel flow), or simulated in more detail in two dimensions (2D) on the basis of local topography. When the sewer system is surcharged, flow changes from open-channel flow to pressurized flow, and the model used must be capable of handling such changes.

Furthermore, when hydraulic grade line elevation exceeds the ground elevation at a node, excess flows may spill on the ground surface and be routed further downstream in the catchment, where it may re-enter the sewer system through another node. Such conditions cannot be described by 1D models. To account for dual (surface/subsurface) drainage, it is recommended to use combined surface runoff / sewer system models (1D/1D or 1D/2D, e.g. Leandro *et al.* 2009), which address these issues and simulate the dynamics of surface flooding in detail. In general, it is also possible to use a 1D/3D model, if the green/pervious parts of the urban area are dominant or need more attention. Then the infiltration and evapotranspiration processes should be described in more detail.

Finally, detailed discussions and reviews of urban rainfall/runoff modelling processes can be found elsewhere (Zoppou 2001; Elliot and Trowsdale 2007; Fletcher *et al.* 2012).

2.4.2 Climate change and urban drainage

The early approximations of climatic changes were rather simple, developed for annual means of temperature and precipitation, and applied in the form of constant climate factors (CFs) used as multipliers of historical data (Nemec and Schaake 1982). Subsequently, methods for distributing the annual changes during the year were developed. One of such statistical downscaling methods, referred to as the Delta Change Approach (or method, DCM) was proposed by Lettenmaier *et al.* (1999) and later applied to rainfall depths in the catchment hydrology (e.g., Hay *et al.* 2000, Xu *et al.* 2005) and in urban drainage modelling (Semadeni-Davies *et al.* 2008 a;b). The last named studies addressed climatic changes on a monthly basis, and in two groups dividing the rainfall events into small ("drizzle") events and larger ("storm") events, but found very large and variable CFs for Helsingborg on the west coast of Southern Sweden.

The earlier DCM approaches (e.g. Lettenmaier *et al.* 1999; Hay *et al.* 2000; Xu *et al.* 2005) were not well-suited for urban drainage modelling, because of lack of emphasis on rainfall intensities and seasonal variations, and the approach suggested by Semadeni-Davies (2008 a;b) showed very large variations in climate factors within the same season. However, as pointed out by Willems *et al.* (2012b), DCM can be applied to any rainfall characteristic, including intensity, inter-event times, seasonal variations, etc.

National guidelines for using climate factors (CFs) to increase (uplift) historical rainfall are available in a number of countries. For example in Sweden CFs are defined regionally (SWWA 2011a), but in Denmark, CFs are assigned to various return periods of rainfall (Arnbjerg-Nielsen 2012). Constant CFs providing a constant uplift to single rainfall events represent the most common (original) approach to accounting for climate change in urban drainage practice (e.g. Niemczynowicz 1989; Ng and Marsalek 1992; Waters *et al.* 2003; Semadeni-Davies 2004; Ashley *et al.* 2005; Denault *et al.* 2006; Nielsen *et al.* 2011). Numerical values of CFs differ among studies, depending on the region studied, the climate projection used, and the method used to identify factors of change.

When using rainfall time series, rather than single event rainfalls, it is feasible to use a more detailed delta change method focusing on differences in rain volumes (e.g. Semadeni-Davies *et al.* 2008a;b) or intensities (Nilsen *et al.* 2011; Olsson *et al.* 2012). Delta changes can be applied over periods of months (Semadeni-Davies 2006; Semadeni-Davies *et al.* 2008a;b) or seasons (Olsson *et al.* 2012), and dry periods between rainfall events can be also taken into account (Olsson *et al.* 2012). Other less common methods are based on the identification of trends in measured historical data (e.g. Denault *et al.* 2006), or climate analogue techniques (e.g. Arnbjerg-Nielsen 2012; Hernebring 2012).

Uncertainties involved in using climate models and emission scenarios are difficult to assess, and consequently, it has been recommended to use an ensemble of climate models and scenarios (Willems *et al.* 2012a;b). This approach was adopted in the IPCC Special report (IPCC 2012), which suggested that in Northern Europe, today´s rainfall of a 20-year return period would have a return period of 10 years (on average) in the future (2081-2100). In Sweden, this approach would entail CFs ranging from 1.25 to 1.26 (Dahlström, 2010) and such values are similar to those from the climate projections recently published by SMHI [Swedish Meteorological and Hydrological Institute] (Olsson and Foster 2013). The latter report provides future CFs for Sweden on the basis of an ensemble of 6 climate projections for a 10-year return period rainfall and climate uplift factors of 1.07-1.35 (average of 1.23), for rainfall duration of 30 min and the time period of 2081-2100 (Olsson and Foster 2013).

All these factors suggest that the average increases of future rainfalls in Northern Europe and Sweden are close to 1.25 (for the future time period 2071-2100), which agrees with the current urban drainage recommendations (SWWA 2011a) for the same time period, in the range of 1.05-1.30, depending on the specific location in Sweden. Rainfalls adjusted by these CF values can then be used in computer simulations of drainage systems to gain some knowledge of system performance in the future.

2.4.3 Urban drainage responses due to climate change

Before 2001, which is the year when the IPCC third climate change assessment report was released, there were very few references on UDS performance responses to future climate changes (i.e., in both combined and separate stormwater systems), e.g., Niemczynowicz 1989 and Schreider *et al.* 2000. Even in 2007, when the IPCC fourth assessment report was released, the number of references in this field was still limited (e.g., Semadeni-Davies 2003; Waters *et al.* 2003; Semadeni-Davies 2004; Ashley *et al.* 2005; Denault *et al.* 2006), but has increased much since then. The references listed above focused mostly on UDS performance, and less on the UDS interactions with urban area flooding. Later, these interactions gained more and more on importance (e.g. Price & Vojinovic 2008; Gersonius *et al.* 2012; Zhou *et al.* 2012), also as a result of development of more advanced and detailed approaches to UDS modelling.

Although the specific results of UDS responses due to climate changed rainfalls should not be directly compared, as they are based on different catchments and climatic regions, some tendencies in such results of general interest are presented below:

- Niemczynowicz (1989) is one of the earliest references concerning climate change impacts on urban drainage, which were addressed in Lund (Southern Sweden) in a 1769 ha catchment with an imperviousness of 30%. Rainfall inputs for runoff simulations were based on the Chicago design storm (CDS) and further increased by 10, 20, and 30%. The results showed an increase in combined sewer overflows (CSOs), an increase of the total inflow to the sewerage system, and also significant flooding problems in the sewerage network when rainfall intensities increased by 20 and 30%.

- Waters *et al.* (2003) suggested that the existing urban stormwater system of the Malvern subdivision in Burlington (Canada) may not be capable of conveying the runoff flows resulting from increased rainfall due to climate change, without some inconveniences or flood damages. The Malvern catchment is 23 ha with about 34% of the area being impervious. An increase of the design storm intensity of 15% was used as a rainfall input, which resulted in an increase in runoff volume and in peak discharge, and caused 24% of the pipes to surcharge. The authors also discussed various potential adaptation measures, e.g., disconnection of all or one half of roof areas, which could decrease peak discharge by between 13 - 39% (the higher value corresponds to the disconnection of all the roofs).

- Ashley *et al.* (2005) suggested that potential effects of climate change on urban property flooding were likely to be significant in the future, according to a study performed in the UK. Four catchments, representing three different types of catchments, were studied concerning the potential impacts of climate change on their drainage. In two cases, flooding within the urban area was noted; coincident flooding involving local river systems was reported in one area, and coincident flooding involving tidal effects was reported in the last area. The sizes of the catchments ranged from 3934 to 727 ha (with 15-34% imperviousness). Flood damages were expressed as the number of properties affected and the estimated economic damage costs (Ashley *et al.*, 2005).

- Semadeni-Davies *et al.* (2008a;b) conducted two studies of the combined and separate stormwater UDSs in Helsingborg (Southern Sweden) with similar results of increasing influence by climate change. The results showed, e.g., increased future WWTP inflows and CSO volumes. Total flow volumes in Lussebäcken Creek (carrying separate stormwater) also increased due to changes in the future climate. The rainfall input for the modelling was a measured rainfall time series that was uplifted according to the changes projected by RCA0 (Rossby Centre Atmosphere Model, SMHI) and downscaled by a Delta change method, after separating storms from drizzle events. In this study, progressing urban development was also included among the scenarios, and contributed to greater impacts (Semadeni-Davies *et al.* 2008a;b)

2.5 Other future changes of urban catchments and their drainage

Future changes in urban catchments and their drainage networks as well as changes in drainage boundary conditions (e.g., increased water levels in receiving waters) will affect the hydraulic performance of drainage systems, but were deemed beyond the scope of this thesis. The most pronounced catchment change is caused by progressing urbanization (increasing imperviousness), which will increase the magnitude of climate change impacts on the runoff and the hydraulic performance of drainage systems both locally and in the whole catchment (e.g. Semadeni-Davies *et al.* 2008a;b; Tait *et al.* 2008).

Deterioration and siltation of storm sewers will reduce sewer capacities, by increased roughness and reduced cross-sectional areas, and such issues can be addressed by computer modelling. However, some of these effects can be reversed by maintenance activities, e.g., by removal of sediments, or by other measures serving to reduce the hydraulic roughness of pipe walls (Tait *et al.* 2008). Higher water levels at drainage outlets (at the sea, lake or river) may lead to the propagation of backwater into sewer outfalls and will reduce the drainage system capacity; in some cases it may become necessary to maintain stormwater drainage operation by pumping. Higher groundwater tables may increase infiltration of extraneous water into sewers and reduce their conveyance capacity. The occurrence of such situations would depend on local hydrogeological conditions and the condition of the sewer system, which may be adversely impacted by cracks, damaged joints, root intrusions etc.

3 Methods

The choice of methods used in this thesis project was largely given by the overall study objective: advance the understanding of urban stormwater systems response to, and their hydraulic performance reflecting, future climate changes, including the future rainfall regime, by means of urban rainfall/runoff modelling.

The papers included in this thesis are closely linked together as shown schematically in Figure 8 below. Starting on the top, drainage response parameters to climate change impacts were developed in paper V and applied in papers II, III and VII. In parallel, the DCM was refined in paper I and applied in papers II and III. Finally, the analysis of runoff formation role of green areas was undertaken in paper VII and its results were built upon in paper IV, and to a lesser extent in paper VI.

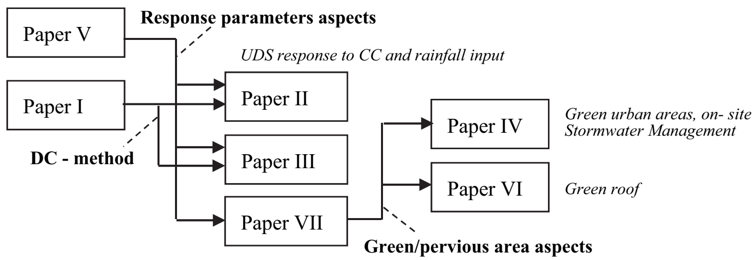

Figure 8. Organization of thesis papers and their linkages, with respect to flow of information and results (for more information about papers, see the List of papers).

3.1 UDS response parameters

Early in the thesis project, the needs for detailed and accurate descriptions of the response of the UDS to climate change processes were identified, and addressed in a literature study, which was presented later at the ICUD conference in Edinburgh 2008 (paper V). The study started with examining the UDS performance and sustainability indicators, and focused on the three main aspects: (a) performance of stormwater UDS, (b) changes in performance related to hydraulic loading, and (c) climate change influences on rainfall-runoff processes.

3.2 Refinement of the Delta change method (DCM)

The Delta change method (DCM) is a statistical downscaling method (Lettenmaier *et al.* (1999)) which was applied to rainfall depths in the catchment hydrology (e.g., Hay *et al.* 2000, Xu *et al.* 2005) and in urban drainage modelling (Semadeni-Davies *et al.* 2008 a;b). Those earlier DCM approaches were not well-suited for urban drainage modelling, because of lack of emphasis on rainfall intensities and seasonal variations. Furthermore, as used by Semadeni-Davies (2008 a;b), DCM showed large variations in climate factors within the same season. However, as pointed out by Willems *et al.* (2012b), DCM can be applied to any rainfall characteristic, including intensity, inter-event times, seasonal variations, etc., which was further emphasized in this thesis (paper I).

The needs for further refinement of DCM to produce future rainfall inputs for urban drainage modelling stemmed from the findings reported in the literature: (a) Requirements on fine temporal and spatial resolutions of rainfall inputs in modelling urban catchments (e.g. Schilling 1991), (b) the importance of rainfall intensity for computing urban runoff peak flows and sizing runoff conveyance elements (e.g., ASCE 1992; Zhou and Schilling 1996), and (c) occurrence of high intensity bursts in local convective storms occurring during summer months in Sweden (Dahlström 1979; Dahlström 2010; SWWA 2011a). Another reason for refining DCM was the fact that the use of rainfall time series, instead of single event rainfalls, would address long-term influence of changing climate on the UDS, as well as on catchment hydrological processes (e.g., identification of initial soil moisture conditions).

Thus, the refinement of DCM for urban drainage modelling applications focused on describing changes in future rainfalls with respect to: (a) intensity of rainfalls; (b) seasonal differences, and (c) the use of high resolution rainfall time series.

In general, DCM is based on the following assumptions:

- The bias in both future and control periods is the same, and cancels out when calculating CFs.
- The future climate data set represents well the future climate.
- The change factors for future rainfall derived from the climate model data apply to the measured rainfall data as well, although the spatial resolution is not the same (areal vs point data), and a new assumption (for the refined DCM):
- The earlier DCM approach also applies to rainfall intensities (divided according to seasons over the year), even though the extreme events are generally less well represented by the climate models.

The processing of climate data (e.g., the smoothing of climate factor variations by averaging over percentiles, and CF applications to 30-min segments of tipping bucket rainfall data) is further described in the results section and exemplified on a data sample from south-eastern Sweden (Kalmar). The results from this section were used as inputs to papers II and III.

3.3 Urban test catchments studied

Studies of hydrological responses of catchments, and their water resources and infrastructures, to climatic changes are generally done by modelling hydrology of specific catchments, as first time proposed by Nemec and Schaake (1982) and later done by many others (listed in Willems *et al.* 2012b). This thesis project focused on urban areas and their drainage systems, and the test catchment had to be selected accordingly, using the following criteria: (1) representativeness of typical Swedish residential areas (with potential transferability of results to other locations); (2) availability of rainfall/runoff data, including a rainfall record with high temporal resolution (tipping bucket, 0.2 mm), which was statistically evaluated and published (Hernebring 2006); (3) Occurrence of flooding in the catchment (year 2003), and (4) availability of a rainfall/runoff model set up for the catchment.

In practice, the test catchment selection often follows a compromise: between selecting catchments with characteristics allowing applicability to large classes of urban areas, and the opportunistically selected catchments, for which physiographic and hydro-meteorological data are available. The latter approach was followed here, with the choice of a Kalmar catchment (used in papers II, III, VII; see Table 4 and Figure 9 for more details).

Additionally, a green area test plot was also used in modelling (without considerations of an UDS), with the model set up parameters representing the attributes of general urban green areas in Sweden. Finally, the selections of test areas were completed by a green roof example, used in conjunction with climatic data from four Swedish climatic regions (Table 4 and Figure 9).

Table 4. Characteristics of study areas.

	Kalmar – small	**Kalmar - large**	**Green area*** **	**Green roof***** **
Location/ Climate	Southern SWE	Southern SWE	SWE general	Four regions from south to north of SWE
Catchment area	54 ha*	227 ha**	0.02 ha	-
Sewers/nodes	440 nodes	440 nodes	-	-
Population	3 000, suburban	3 000, suburban	-	-
Imperviousness	37%	12% (37%)	0%	-
In papers:	*II*	*III, VII*	*IV*	*VI*

* 1D model was set up for the areas with direct influence on runoff draining into the urban drainage system in the Kalmar catchment.

** 1D/3D model was set up for all the areas possibly contributing runoff in the Kalmar catchment, including green areas within the catchment, but with a secondary influence on catchment runoff and the urban drainage system.

*** Model set up of a small green urban area (10 x 20 m), representing a typical size of a front lawn, backyard, or other small urban green area (3D-model).

**** Green roof study, based on climate in four regions: Skåne (South), Gävleborg (Middle), Värmland (Middle), Norrbotten (North), (Figure 9).

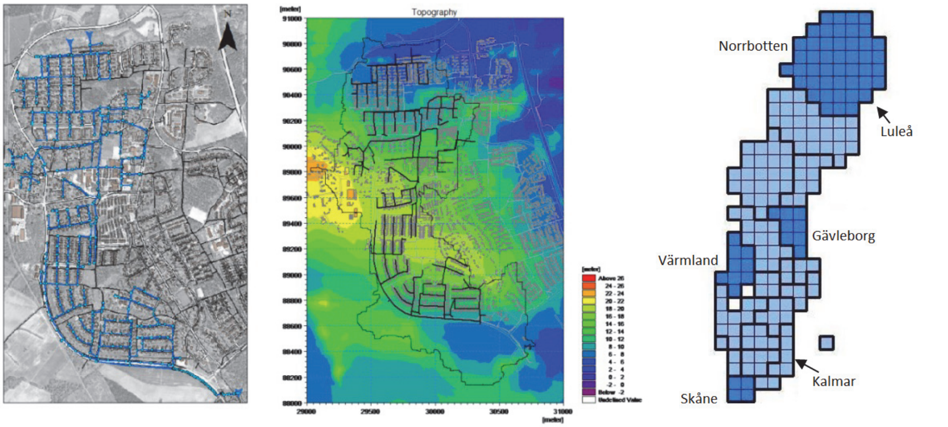

Figure 9. Study areas: (a) Kalmar catchment UDS (Left panel, from paper III), (b) Kalmar catchment topography (Middle panel, from paper III), and (c) Four regions of Sweden (Right panel, from paper VI).

3.4 Rainfall inputs

Two types of rainfall input are commonly used in runoff simulations: time series (TS) or single events (SE) of various types (e.g., measured rainfall events or design storms).

For the Kalmar region, rainfall data collected by a tipping bucket (0.2 mm) from 1991 to 2004 (statistically evaluated by Hernebring 2006) were used in this thesis (Figure 10).

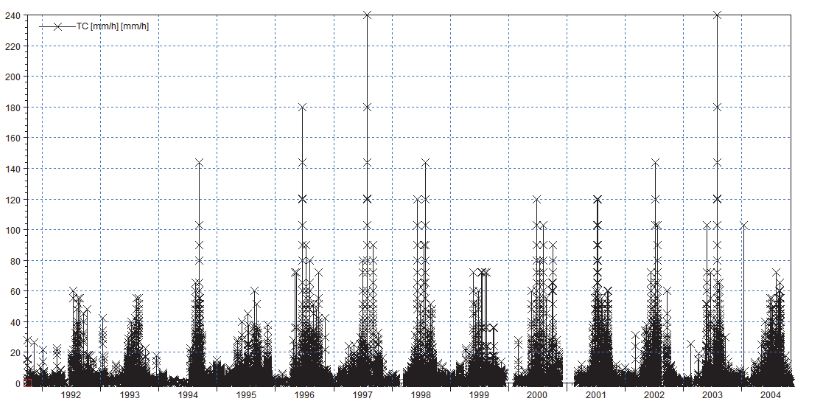

Figure 10. Kalmar rainfall time series 1991-2004.

From the Kalmar rainfall time series, containing about 700 rainfall events (Hernebring 2006), the most intense events were selected for further analysis using an inter-event time of 2 h and excluding events with less than 0.2 mm of rainfall and intensities < 0.1 mm/h. For each rainfall event, the maximum rainfall intensities for eight durations (5, 10, 20, 30, 40, 60, 90, 120 min) were compared with the current Swedish rainfall statistics (Dahlström 2010). This led to the selection of five most intense events, with average return periods of 2 years or more. Among these five, storms 1994-09-09, 1996-06-19, and 2002-07-24 were rated as having a 2-year return period, 5 years in the case of storm 1997-07-27, and finally almost 100 years in the case of storm 2003-07-29 (Table 5). The rainfall hyetographs of these five rainfalls are shown in Figure 11.

Table 5. Characteristics of the five most intense rainfall events in the Kalmar rainfall time series (1991-2004), with return period of about two year or more. From paper III.

Rainfall events				Return periods (y) associated with storm rainfall intensities of ten durations (5-120 min)									
	D_{tot} [h]	P_{tot} [mm]	T_{avg} [y]	5 [y]	10 [y]	15 [y]	20 [y]	30 [y]	40 [y]	50 [y]	60 [y]	90 [y]	120 [y]
1994-09-09	8.08	27.6	2.0	0.7	1.3	1.8	2.3	2.5	2.7	2.2	2.3	2.2	2.1
1996-06-19	2.01	12.8	2.0	4.2	2.9	2.5	2.0	1.4	1.2	1.0	0.8	0.7	0.6
1997-07-27	2.32	15.4	5.4	13.1	8.1	6.2	5.3	3.7	2.8	2.2	1.9	1.3	1.0
2002-07-24	0.87	12.0	2.1	2.0	3.6	3.2	2.6	1.8	1.3	1.1	0.9	0.6	0.5
2003-07-29	6.98	93.0	90.1	21.4	43.5	59.4	62.8	81.0	124.4	157.4	171.2	144.2	125.8

D_{tot} - total duration, P_{tot} – total rainfall depth, T_{avg} - average return period (5-60 min)

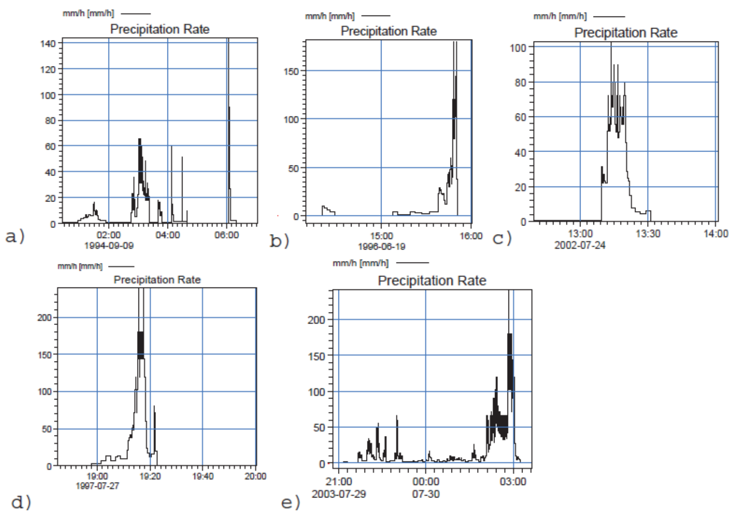

Figure 11. Five highest rainfall intensity events extracted from the measured Kalmar rainfall time series, 1991-2004 (from paper III).

Single rainfall events, referred to as design storms, are commonly used in design of UDSs. Two of such storms, Block rainfall and CDS, were presented earlier in Figure 6 in the Background chapter, and were also used in this thesis.

From the theoretical point of view, design storms are subject to various criticism, which mostly focuses on the fact that it is unlikely that the design rainfall would produce a calculated runoff peak of the same return period (Marsalek and Watt 1984). This is particularly marked in the case of the CDS approach, in which all the maximum intensities of various durations are assigned to one single event (Alferi *et al.* 2008; Watt and Marsalek 2013), which contradicts experience from preparation of IDF curves, in which maximum intensity segments of the same return period come from different rain storms. Thus, the return period of the CDS event is likely higher than indicated by its definition. However, from a practical point of view, design storms can be seen as representing a certain design convention and their widespread use continues unabated in many countries (Watt and Marsalek 2013). In Sweden, SWWA national recommendations specify the CDS rainfall for design of new systems (SWWA 2011a) and Block rainfalls for evaluating the capacity of existing systems. Therefore, these design rainfalls were also included in this thesis.

To address future climate changes, climate factor uplifts were applied to these rainfalls. For the measured rainfall time series, both a delta change method ($DCM_{i,s}$, from paper I) with uplift factors ($CF_{DC(i,s)}$) as well as a constant uplift factor ($CF_{CON(1.2)}$) were used. For the design storms, a constant uplift factor was used ($CF_{CON(1.2)}$).

3.5 Runoff simulation models used

Future climatic conditions related to the urban stormwater management need to be addressed by computer simulations of future climate change scenarios by urban runoff models (e.g., Borris *et al.* 2013). Any of the current well-established advanced models (including the DHI models used in this thesis) is capable of simulating the generation of urban stormwater runoff for broadly varying conditions, with a high level of certainty (Zoppou 2001). Model software used in all the modelling work in this thesis was based on the DHI models: Mouse-MikeUrban (1D), MikeShe (3D), and Mouse coupled with MikeShe (1D/3D) (Table 6). In general, other types of software similar to DHI models (SWWM, InfoWorks, and others) could have been also used.

Surface runoff from urban areas directly connected to the piped UDS was computed, with the Time-area method, the flooding of urban areas and overland flow in 2D simulations (part of the 3D approach) was computed with a Diffusive wave simplification of St. Venant's equations, and the pipe flow (1D) was computed by means of St. Venant's Dynamic wave approach (Table 6).

Infiltration was computed either by a simplified approach based on a 2-Layer Water Balance approach (DHI 2011), which is somewhat similar to a percentage runoff/infiltration approach; or by a detailed approach based on the Richards Equation (Richards 1931) (Table 6). The latter approach is physically based and assumes the validity of the Darcy's Law for both saturated and unsaturated flows (Chow *et al.* 1988; Beven 2001). Actual evapotranspiration was either assumed as a fixed value (i.e., a simplified approach in Mike She) (DHI 2011), or calculated with a method based on Kristensen and Jensen (1975) (DHI 2011).

A general problem in urban drainage modelling is the fact that the calibration and verification of models is usually based on data collected for frequent rainfall events, but rarely such datasets contain extreme events. Hence, even calibrated models can be biased. However, there is a great deal of experience with applications of these models and guidance for the selection of model parameter values, which increases the confidence in modelling results (Fletcher *et al.* 2012). In this thesis, the Kalmar catchment model was calibrated using measurements of rainfall and pipe flow, and verified, showing good agreement between measured and modelled data (for more details, see paper II). The green area plot was not calibrated against measurements of soil moisture conditions, but was quality checked (paper IV).

Table 6. Modelling approaches used in individual papers with respect to the types of rainfall inputs, climate factors, equations of individual processes and the software used.

Paper	Model	Rainfall	Climate Factor	Runoff	OL	Pipe flow	Inf	ET	Software
II	1D	TS	$CF_{DC(i,s)}$	TA	-	SV-Dy	-	-	MikeUrban (Mouse)
III	1D/3D	SE:Block	$CF_{CON(1.2)}$	TA	SV-Di	SV-Dy	2LW	2LW	Mouse/ MikeShe
III		SE:CDS	$CF_{CON(1.2)}$						
III		SE:Measured	$CF_{CON(1.2)}$						
III		SE:Measured	$CF_{DC(i,s)}$						
VII		SE:CDS	$CF_{CON(1.2)}$	“	“	“	“	“	“
IV	3D	SE: CDS	$CF_{CON(1.2)}$	-	SV-Di	-	RE	K&J	MikeShe

OL: Overland flow (2D), Inf: Infiltration, ET: Evapotranspiration, TS: time series rainfall, SE: Single event rainfall, CDS: Chicago design storm, climate factor CF: constant - $CF_{CON(1.2)}$ and Delta change - $CF_{DC(i,s)}$, TA: Time Area approach, SV-Di: StVenant, Diffusive wave, SV-Dy: StVenant, Dynamic wave, 2LW: 2LayerWaterBalance approach (DHI 2011), RE: Richards Equation (Richard 1931), K&J: Kristensen and Jensen approach (1975).

3.6 Modelling studies and input parameters

3.6.1 UDS response to various types of rainfall and climate uplift method inputs

In the first UDS study of the Kalmar catchment, a continuous modelling approach was chosen (with a 1D model set up), using both today's climate rainfall time series (Figure 10, and Figure 11) and a future rainfall derived with $DCM_{i,s}$ (according to the method described in paper I). In the original paper three future time periods were studied, but only one of these is included among the results presented in this thesis.

In the second study of the Kalmar catchment, a refined modelling approach was used (1D/3D) with single event rainfall inputs to reduce the computation times. Three main comparisons were made based on this study:

- Block and CDS design rainfalls: the current and future climates (the latter described with a constant climate factor $CF_{CONS(1.2)}$).
- Block and CDS design rainfalls and the selected measured rainfalls from a time series: the current climate.
- Selected rainfalls (from a measured time series) with two different types of climate uplifts: the $DCM_{i,s}$ (according to the method described in paper I) and a constant climate factor uplift ($CF_{CONS(1.2)}$).

Rainfall data for the five most intense rainfall events in the Kalmar time series (1991-2004, Figure 10), as well as the CDS and Block design rainfalls used in paper III, are shown in Table 7, for both the current and future climates. The future rainfalls were derived by two methods: a constant climate factor ($CF_{CON(1.2)}$ =1.2) and the $DCM_{i,s}$ ($CF_{DC(i,s)}$).

Table 7. Input rainfall characteristics, as used in paper III (and CDS rainfalls in paper IV).

			-		$CF_{CON(1.2)}$		$CF_{DC(i,s)}$	
Rainfall	T* (y)	D_{tot} (min)	P_{tot} (mm)	I_{max} (mm/h)	P_{tot} (mm)	I_{max} (mm/h)	P_{tot} (mm)	I_{max} (mm/h)
Block	2	30**	12	25	15	30		
Block	5	30**	17	33	20	40		
Block	10	30**	21	42	25	50		
Block	100	30**	44	89	53	107		
CDS	2	120	19	66	23	80		
CDS	5	120	25	90	30	108		
CDS	10	120	32	113	38	135		
CDS	100	120	66	242	79	291		
1994-09-09	2	485	27	144	33	173	41	183
1996-06-19	2	121	13	180	15	216	14	218
1997-07-27	5	139	15	240	19	288	18	283
2002-07-24	2	52	12	103	14	123	14	121
2003-07-29	100	419	96	240	115	288	109	305

D_{tot} – total duration. P_{tot} – total rainfall depth. I_{max} – maximum intensity. CF – climate factor.

* T – Return period, specific for design storms and its equivalent for measured events.

** 30 min duration Block shown as an example, for the Blocks in a series of durations of 5, 10, 15, 20, 30, 40, 50, 60, 90 and 120 min.

3.6.2 UDS Sensitivity analyses in the Kalmar catchment

Simple sensitivity analyses were performed (in the Kalmar catchment) addressing UDS responses to changes in green area runoff caused by changes in: (1) rainfall; (2) evapotranspiration; (3) infiltration capacity of two soil types; and, (4) elevated groundwater tables (see Table 8 for more details).

Table 8. Sensitivity analysis of the Kalmar catchment runoff, scenarios: baseline, high precipitation, high and low evapotranspiration, high and low infiltration capacity, and high groundwater level (from paper VII).

Run	Scenario	T [years]	I_{max} [mm/h]	ET [mm/d]	Soil character	K_s [m/s]	θ_s [-]	θ_{fc} [-]	θ_w [-]
1	Baseline (BL)	10	69.6	3	"moraine"	$5*10^{-6}$	0.4	0.3	0.05
2	Prec High (PH)	10, $CF_{CON(1.2)}$	83.6	3	"moraine"	$5*10^{-6}$	0.4	0.3	0.05
3	ET Low (EL)	10	69.6	0	"moraine"	$5*10^{-6}$	0.4	0.3	0.05
4	ET High (EH)	10	69.6	6	"moraine"	$5*10^{-6}$	0.4	0.3	0.05
5	Infiltr High (IH)	10	69.6	3	"sand"	$5*10^{-4}$	0.4	0.1	0.02
6	Infiltr Low (IL)	10	69.6	3	"bedrock"	$1*10^{-10}$	0.3	0.1	0.05
7	GW High (GW=0)	10	69.6	3	"moraine"	$5*10^{-6}$	0.4	0.3	0.05

T –Rainfall return period, I_{max} - Rainfall max intensity, ET – Evapotranspiration, θ_s – saturated soil moisture content, θ_{fc} – soil moisture content at field capacity, θ_w – soil moisture content at wilting point, K_s – Saturated hydraulic conductivity, Prec – Precipitation, ET – Evaporation/Evapotranspiration, Infiltr- Infiltration capacity, GW – Ground water level.

3.6.3 Green area model set up

The size of the urban green area test plot (10 x 20 m), which was modelled using the MikeShe 3D set up (the manuscript/paper IV), was similar to the size of plots used by others, e.g., in modelling grassed swales and filter strips (Deletic 2001; Deletic & Fletcher 2006), biofilters (Daly *et al.* 2012) and soakaways (Roldin *et al.* 2012a; 2012b; 2013). These types of areas may serve as potential sites for future adaptation measures in the form of green infrastructure (GI, also called BMPs, SUDS, LID, etc.).

The model input data used in the green plot set up are shown in Table 9, and with respect to soil type characteristics, in Table 10. For more details, see paper IV.

Table 9. Model parameter set up for paper IV.

Model parameter			**Comments:**
Size	200	m^2	Similar (small) size plots were used e.g. in modelling grassed swales and grassed filter strips (Deletic 2001; Deletic & Fletcher 2006), Biofilters (Daly *et al.* 2012) and Soakaways (Roldin *et al.* 2012a; 2012b; 2013).
Slope	5	%	
Roughness, Manning *M**	6	-	Values from 1.5 to 10 used in other research for Grassed areas, e.g. Deletic (2001) M=1.5 for Dense Grass (n=0.65), and M=10 for Sparse Grass (n=0.1). Bäckström (2002) used similar values studying Grassed swales in Luleå (north of Sweden), M=2.9, M=6.3 and M=6.7
Detention storage	2	mm	Deletic (2001) surface retention with grass 2.7 mm (smooth) and 4.2 mm (rough). Mohamoud (1992) typical tilled plots detention storage 0.77-2.64 mm.
Vegetation: LAI**	3		Swedish summer season values, from DHI veg. database
Vegetation: Root depth	600	mm	Swedish summer season values, from DHI veg. database
Pot. Evaporation/Evapotransp.	3	mm/d	Swedish summer season values, Pennman calculations for 1961-1978 (Eriksson 1981).
Ground water level (depth)	-2	m	

*Roughness Manning *M (M=1/n)* similar to Strickler *K (K=1/n)*.

**LAI – Leaf Area Index.

Table 10. Soil characteristics. θ_S – saturated soil moisture content, θ_{fc} – soil moisture content at field capacity, θ_w – soil moisture content at wilting point, θ_r – residual soil moisture content, n – Averjanov soil coefficient, K_s - Saturated hydraulic conductivity (from the DHI soil database).

Soil	**Bulk density** [kg/m3]	θ_S [-]	θ_{fc} [-]	θ_w [-]	θ_r [-]	**n** [-]	K_S [m/s]
Fine Till	1700	0.305	0.230	0.02	0.010	10	$1.5*10^{-7}$
Intermediate Till	1700	0.470	0.305	0.03	0.018	8	$1*10^{-6}$
Coarse Till	1700	0.380	0.300	0.04	0.030	5	$5*10^{-6}$

3.6.4 Green roof study

The study of green roofs served as an example of adaptation measures taking advantage of hydrological characteristics of green infrastructure. The specific study directions were based on the following findings:

1. A literature study revealed that green roof performance depends on the climate, and consequently, five different European climates were considered: Very Cold, Cold, Mild, Warm, and Very Warm.
2. Future changes in climate (precipitation and temperatures) were identified by comparing today's climate (control period 1961-1971), and a future climate period: 2100 (2091-2100), for four regions in Sweden: Skåne, Gävleborg, Värmland, Norrbotten (from the south to the north). The changes in climate data were described by seasonal averages, using the regional atmospheric climate model RCA3 (Kjellström *et al.* 2005), based on the global climate model ECHAM4 (Roeckner *et al.* 1996) and Emission scenario A2. The original monthly climate data had a spatial resolution of 50*50 km.
3. The four regions in Sweden were classified according to different climate types (defined in (1)) for all the annual seasons.
4. The green roof potential reduction of incoming precipitation was calculated on the basis of information listed under items 1-3.

4 Results and Discussion

The results presented in this section are organized according to the Thesis objectives and expected outcomes (Section 1.1) in the following parts:

- UDS response parameters
- Climate model information adaptation for urban drainage modelling needs (Delta Change method refinement)
- Influence of future climate rainfall inputs on UDS performance, measured by UDS response parameters
- Potential influence of green areas on simulated urban runoff and UDS performance, in a future climate, and an example of climate change adaptation using green roofs.

4.1 UDS response parameters due to climate change

From the literature study in paper V, a classification of UDS response parameters was developed reflecting a timeline of events and responses, before the exceedance of the UDS capacity occurs, during the overloading, and after, dealing with the consequences of the event.

4.1.1 Classification

In this thesis, the following classification of the performance response parameters (PRPs) was adopted, for reasons further explained below: (A) indicators of the system performance, (B) indicators of the system capacity exceedance, and (C) indicators of consequences resulting from capacity exceedance (Table 11). Other PRPs, which may be of interest in specific studies, will be addressed here only briefly.

Table 11. Classes of response parameters (PRPs), based on the timing of their occurrence, characteristics and consequences with respect to UDS (from paper V)

	Before the event	During the event	After the event
System performance	A	-	-
Capacity exceedance	-	B	-
Consequences	-	-	C

The parameters related to the UDS capacity exceedance received special attention in this thesis, particularly in papers II and III, in which UDS responses to climate change impacts were examined. The capacity exceedance was also related to a "safety margin approach" (SMA), which was discussed more in the above papers.

Referring to Table 11, firstly, it is important to evaluate the system performance before an event causing hydraulic overloading occurs, so that the normal daily UDS operation can be assessed. When heavy rainfall and system overloading occurs, the system will respond to this event and its capacity during such a response needs to be evaluated. When the UDS capacity (i.e., flow capacity) is exceeded, then there will be various consequences in the UDS and in the catchment (e.g., inundation of surfaces and basements, CSOs, etc.) and these consequences can be classified according to their character.

4.1.2 Safety margin approach (SMA)

SMA can be compared with other approaches related to the management of climate change impacts on UDS and urban area flooding, as e.g., in the "Three Points Approach" (3PA) (Geldof and Kluck 2008; Fratini *et al.* 2012). In the 3PA, the domain (1) focuses on design events (which is analogous to category B in SMA), domain (2) focuses on the extreme rainfall events (similar to category C in SMA); and, domain (3) focuses on relatively frequent events just below the design capacity (similar to those in category A in SMA).

In Berggren's papers (papers II, III and especially VII), focus is on the hydraulic UDS performance related to a safety margin approach, in which the exceedance of a safety threshold level just below the hydraulic capacity exceedance (i.e., water spillage on catchment surface) is deemed to be helpful in judging the UDS safety. This thesis focuses on minor drainage, UDS and the catchment characteristics, and hence the flood risk management and major drainage issues (included in the 3PA) are outside the scope of the thesis and have not been addressed. Further development of the 3PA in a study published by CIRIA (2014) in UK (also Digman *et al.* 2014) suggests addition of a fourth domain focusing on marginal "exceedance" of design events, which is also in line with suggestions in paper V and fits the focus area of this thesis.

Another example of addressing the hydraulic overloading of UDS is the Mainstreaming Approach, which combines underground and above ground flooding and urban drainage system performance, focusing on adaptation measures related to future changes in the urban area (spatial planning) as well as climate change (Gersonious *et al.* 2012). The Mainstreaming method use of response parameters, as applied in Dordrecht (the Netherlands), bears a great deal of similarity with the SMA used in this thesis. For example, the mainstreaming method compares the impacts by using water levels in manholes and relating them to a "freeboard" level (as commonly done in hydraulic design), which is similar to the "safety margins" proposed in Berggren (2007 – licentiate thesis), as well as in papers (II and III) and relates water levels in manholes to the ground elevation or a critical level (0.5 m) below the ground. The "No freeboard" state in Gersonious *et al.* (2012) is comparable to the state of full surcharge, i.e., water levels just reaching the ground elevation, specified in Berggren (2007) and paper II.

Further support of the SMA can be found in Nie *et al.* (2009). These authors suggest establishing response parameters based on similar principles and addressing pipe flow (and surcharged pipes), hydraulic grade line pressure elevation (similar as the water levels in nodes) exceeding different levels within the system (e.g., focusing on the basement levels, as the sewer system in their study was combined), and further adding consequences demonstrated in the urban area, including combined sewer overflows. Berggren in her licentiate thesis (2007) already addressed the critical level exceedance, which was further developed in paper V, and the suggestions made by Nie *et al.* (2009) further validate these choices of response parameters as relevant in the study of impacts on UDS, especially with the respect to climate change.

A summary of response parameters from 33 references found in the literature, classified according to the Safety Margin Approach groups A - C, are listed in Table 12. The references cited focused mainly on climate change impacts on UDS, except for the first four (Kiefer and Chu 1957; Packman and Kidd 1980; Arnell 1982; Beaudoin 1983), which were included in the summary to get a broader historical overview of the UDS response parameters.

Table 12 emphasized the references focused on runoff quantity issues (i.e., the topic of this thesis), but some examples of runoff quality responses were also given (e.g., Niemczynowicz 1989; Butler *et al.* 2008; Semadeni-Davies *et al.* 2008a; and, Borris *et al.* 2013). Urbanization changes are also sometimes included in studies of climate change impacts (e.g., Semadeni-Davies *et al.* 2008b; Mott MacDonald 2011; Berggren *et al.* 2012b) and indicate the great influence on UDS performance, mostly because of increased imperviousness of developing urban areas and the resulting amplification of climate change impacts, including more rainfall and runoff from urban surfaces.

The increase in research and publication activities, after about the year 2000, coincides with an increased debate of the climate change issues and the higher occurrence of extreme storms causing flooding in recent years. Also, recent publications indicate more interest in rainfall properties and changes due to climate change, and the interactions with UDS, as summarized in Willems *et al.* (2012b). The majority of all the studies focusing on UDS responses due to climate change (presented in Table 12) used single event rainfalls (SE) as inputs, often in the form of a CDS or Block type of design storms. Time series rainfall (TS) was used less commonly, even though it can better describe specific aspects of climate change impacts, including flood frequencies, discharged volumes, volumes of CSOs, volumes of wet-weather inflows to wastewater treatment plants, and also some water quality aspects, particularly in large scale river catchments (e.g. Schreider 2000). Perhaps one aspect limiting the greater use of rainfall time series and continuous modelling, in combination with more detailed models (e.g. 1D/1D, 1D/2D, 1D/3D), is the computation time.

The results presented in this thesis focused on UDS hydraulic response parameters, and the threshold levels were related to hydraulic exceedances in the UDS and the flooding on the catchment surface. However, an extension of the thesis research questions to the hydrological cycle of the whole urban area would increase the need for definitions of safety margin parameters also for the entire *urban catchment runoff* (i.e., runoff response from impervious and green areas as an input to the UDS, as well as the influence of adaptation actions (BMPs, SUDS, GI, LID), including Green roofs, and the *output discharge regime* (i.e., discharge into the receiving waters, as well as flooding and Major drainage system adaptation actions). These responses could, for example, be related to sustainability aspects such as, technical, economic, socio-cultural, environmental, and public health indicators, and also according to the stakeholders and organizations affected. Further research should look into these issues to assess whether such an approach would improve the understanding of, and facilitate the decision-making regarding, adaptation measures (concerning both quantity and quality of stormwater flows).

Table 12. Parameters of UDS performance response to climate change impacts, including the types of rainfall inputs (Single event rainfalls: SE, or Time series: TS) and parameter classification.

Parameter	**Unit**	**TS/SE**	**References***	**Class****
Catchment				
Runoff:				
Flow rate, Peak flow	[m3/s]	SE	1, 4, 5, ***33***	Input
Volume	[m3]	SE	8, ***29, 33***	Input
UD system				
Pipe flow conveyance:				
Surcharged pipes, number of	[-]	SE, TS(20)	8, 20	A, B
Surcharged pipes, length of	[m]	TS	20	A, B
Pipe flow rate (Q/Q_{full})	[-]	SE,TS(13,24)	***13, 24, 25, 29, 32***	A, B
Manholes/Nodes:				
Number of flooded*** Nodes	[-]	SE,TS(12,13,20, 23,24)	***12, 13,*** 14, 20, 21, 22, 23, ***24, 25,*** 26, 27, ***29,*** 31, ***32***	B, C
Max water levels (also HGLE) in Nodes	[m]	SE, TS(13,24)	***13, 24, 25, 29***	B
--Water level, WL > GSE and CL	[-]	SE, TS(13,20,24)	***13,*** 20, ***24, 25,*** 26, ***29***	B
--Frequency of WL exceeded GSE, CL	[-]	TS	***13, 24***	B, C
--Duration, WL exceeded GSE, CL	[min]	TS	***13, 24***	B, C
Flooding*** volume, spilled at nodes	[m3]	SE, TS(20)	14, 19, 20	B
Discharge:				
Flow rate, Peak flow	[m3/s]	SE, TS(6)	2, 3, 6, 8, 11, 27, ***29,*** 31, ***32***	A
Volume	[m3]	SE, TS(18)	5, 18, 27, 28, ***29,*** 31	A
PRPs specific for Combined systems:				
CSO overflow volume	[m3]	SE, TS(17,20,23)	5, 17, 20, 23, 27	A
Inflow volume to WWTP	[m3]	TS	7, 9, 17	A
Quality aspects				
e.g. TSS, Cu, Zn, Pb, BOD, DO, P_{tot}, NH4N	…	SE, TS(17,30)	5, 14, 17, 30	
Urban area Consequences				
Number of flooded properties, houses, basements	[-]	SE, TS(6,20)	6, 10, 20, 26, 28	C
Depth of flooded*** water	[m]	SE	15, 16, 28	(B), C
Flooded*** area	[m2]	SE	22, ***25,*** 28, ***32***	(B), C
Flooded*** volume	[m3]	SE	22, ***29***	(B), C
Velocity of flooded*** water	[m/s]	SE	16	(B), C
Cost of damage due to flooding***	[EUR]	SE, TS(6)	6, 10, 28, 15, 16	C

*References - 1: Keifer & Chu 1957; 2: Packman & Kidd 1980; 3: Arnell 1982; 4: Beaudoin 1983; 5: Niemczynowicz 1989; 6: Schreider *et al.* 2000; 7: Semadeni-Davies 2003; 8: Waters *et al.* 2003; 9: Semadeni-Davies 2004 10: Ashley *et al.* 2005; 11: Denault *et al.* 2006; **12: Berggren *et al.* 2007a (Novatech 2007); 13: Berggren 2007 (licentiate thesis);** 14: Butler *et al.* 2008; 15: Dawson *et al.* 2008; 16: Price & Vojinovic 2008; 17: Semadeni-Davies *et al.* 2008a (combined system); 18: Semadeni-Davies *et al.* 2008b (stormwater system); 19: Tait *et al.* 2008; 20: Nie *et al.* 2009; 21: Mott MacDonald 2011; 22: Nielsen *et al.* 2011; 23: Nilsen *et al.* 2011; **24: paper II; 25: Berggren *et al.* 2012b;** 26: Gersonius *et al.* 2012; 27: Nie *et al.* 2012; 28: Zhou *et al.* 2012; **29: paper VII;** 30: Borris *et al.* 2013; 31: Olsson *et al.* 2013; **32: paper III; 33: paper IV.**

**Class – Classification: (A): System performance, (B): Capacity exceeding, (C): Consequences. (from paper V)

*** Flooding – referring to fully surcharged nodes and spillage of water onto the catchment surface, WL: Water level, HGLE – hydraulic grade line elevation, similar as WL; GSE: Ground surface elevation, CL: Critical level

4.1.3 PRP selection criteria

Five important criteria serving to select the parameters describing the UDS response to climate change and the system adaptation are summarized below. Ideally, PRPs should possess the following characteristics (from paper V):

1. Fully/yet with a low level of effort describe hydraulic performance of the system (categories A and B)
2. Indicate how close the state of UDS and catchment drainage is to exceeding a critical threshold level (i.e., indicate a safety margin (B))
3. Facilitate the comparison of different catchment areas according to their sensitivity to climate change impacts (B, C)
4. Facilitate the comparison of different adaptation actions in the catchment, in order to determine the best adaptation measures (including their locations) for impact mitigation (B,C), and
5. Provide indications of flexibility, adaptability and robustness of the UDS and catchment system with respect to coping with climate change impacts (-).

The first three characteristics (1-3) are useful in identifying the areas with low safety margins in the early phase of analysis, while feature (3) focuses specifically on the climate change impacts. Feature (4) focuses more on the adaptation phase and identifies potential actions and their influences on the state of the catchment and UDS, and finally, feature (5), representing the last step of analysis, rates how easily a catchment and its UDS can be adapted to future (or ongoing) climate changes. A system with a low safety margin, but many possibilities of implementing adaptation measures in the catchment and the UDS is not as vulnerable to the climate change impacts as the system with a low (or even marginally higher) safety margin but few adaptation opportunities for enhancing the UDS capacity. In this thesis the main focus has been on the first three criteria (1-3).

In Figure 12, the use of different threshold levels is presented graphically in relation to a stormwater manhole (node) elevation, and in Figure 13 a practical example showing stormwater levels exceeding the ground surface elevation (GSE) and causing surface inundation is given.

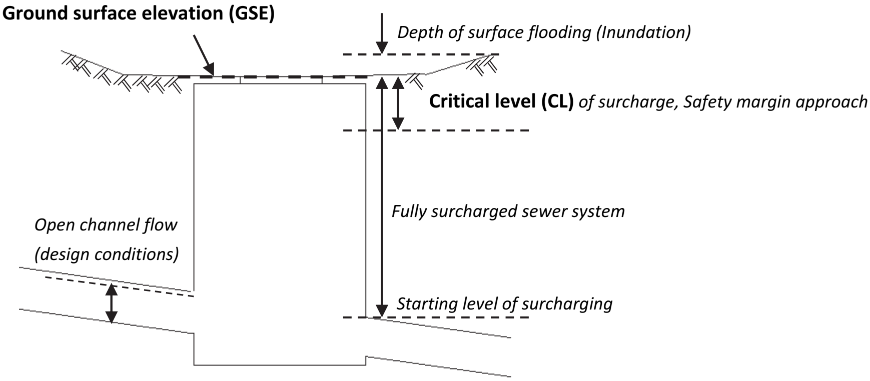

Figure 12. Notation sketch: Different threshold levels in relation to stormwater manhole (node) elevations, Ground surface elevation (GSE) and Critical level (CL).

Figure 13. An example of stormwater level exceedance of the ground surface elevation (GSE) in an UDS (Photo by K. Berggren).

4.1.4 Example of PRPs

Paper II further focused on the hydraulic response parameters, with a specific need of examining climate change impacts on a time series rainfall used in a 1D model set up. In paper III the same ideas were addressed, but using single event rainfalls rather than time series as rainfall inputs, and hence the response parameter set has slightly changed. Additionally, a more refined model set up was used (1D/3D) to facilitate examination of flooded catchment surfaces.

Impacts of increasing rainfall in future climates on catchment flooding and UDS performance can be measured by various parameters, as discussed in paper V. The main reasons for selecting multiple impact evaluation parameters were to provide broad assessments of flooding conditions in sewers as well as on the catchment surface. In the former case, such parameters included e.g., water levels at nodes related to the threshold levels at the node ground elevation and also below the ground elevation at some assigned "critical levels" within the system (as suggested in paper II). In the latter case, the occurrence and extent of flooding on the catchment surface was addressed by using specific threshold levels indicating the level of impact, e.g. the depth of inundation (a water depth of 0.10 m was used in paper III).

This approach allowed a more detailed assessment of differences in catchment/UDS responses for various rainfalls and included the following criteria:

- Numbers of nodes in the system where the ***maximum water level*** during an event exceeds both threshold levels (the ground surface elevation, GSE, and a critical level, CL, e.g. defined as 0.5 m below the ground level). The two thresholds help indicate safety margins in the system.

- ***Pipe flow rate*** (Q/Q_{full}) indicates the UDS performance based on the potential pipe surcharge in the system. The results for the first two criteria can be obtained directly from the Mouse model outputs.

- ***Maximum flooded area***, related to some threshold levels, e.g. 0.10 and 0.15 m above the ground level – the latter was chosen to represent the case when surface water starts to impact on buildings and properties. Flooded areas can be assessed from the MikeShe model outputs, counting the grid cells with the maximum water depths above the threshold levels and multiplying the count by the grid size area.

In Table 13, a summary of the response parameters is presented for both the catchment and its UDS. For urban catchments with a significant presence of green areas, additional parameters describing catchment responses, e.g. water balance and volumetric soil moisture conditions, would bear significance for stormwater management.

Table 13. Three main response parameters used in this thesis: UDS - water levels at nodes (manholes) and pipe flow ratios, and for the catchment, the flooded area.

Parameter			Ex.lev. (Y/N)	Unit
Water level in nodes	Maximum	WL ≥GSE ; ≥CL	(Y/N)	[-]
	Maximum	-	-	[m]
	Frequency: Max	WL ≥GSE ; ≥CL	(Y/N)	[1/y]
	Frequency: Tot	WL ≥GSE ; ≥CL	(Y/N)	[1/y]
	Duration: Max	WL ≥GSE ; ≥CL	(Y/N)	(time)
	Duration: Tot	WL ≥GSE ; ≥CL	(Y/N)	(time)
Pipe flow rate (Q/Qf)	Maximum	-	-	[-]
	Maximum	$Q/Q_{full} \geq 1$	(Y/N)	[-]
Flooded area	Maximum	WL ≥TL	(Y/N)	[m^2]

Ex. lev. – Exceeded level, (Y/N) – Yes/No, GSE – Ground Surface Elevation, CL – Critical Level below ground (e.g. -0.5m), WL – Water Level, TH – Threshold Level above ground (e.g. +0.10 m).

4.2 Delta change method refinement

4.2.1 Delta change method

Climate model data are often characterized by temporal and spatial resolutions, which are too coarse for urban drainage studies requiring high spatial and temporal resolution. For example, Schilling (1991) recommended temporal resolutions of urban rainfall data as high as 1 min and the use of point rainfalls for most catchments, to hydraulically capture runoff peak flows (see also Zhou and Schilling 1996; Bernes *et al.* 2004; Aronica *et al.* 2005; Schellart *et al.* 2012). Hence, downscaling has to be used to produce the data for urban runoff modelling.

A variety of methods for downscaling urban rainfall, using both dynamic and statistical approaches, were presented in the literature (Willems *et al.* 2012b), but their comparative assessment is beyond the scope of this thesis. It is sufficient to say that while dynamic downscaling offers advantages of being physically based, the statistical approaches, including the delta change method, offer finer spatial resolution (needed in urban applications) and are computationally less demanding (Willems *et al.* 2012b). Hence, the majority of climate change impacts studies use statistical downscaling with CFs either constant or variable, derived by DCM and applied either to design storms or to historical rainfall (e.g., Nemec and Schaake 1982; Niemczynowicz 1989; and later many others). The same approach was taken here, focusing on the $DCM_{i,s}$ ($CF_{DC(i,s)}$) and its comparison to the use of constant climate factors and $CF_{CON(1.2)}$ estimates.

Another option would be to use climate analogies (Arnbjerg-Nielsen *et al.* 2012; Hernebring *et al.* 2012), in which climate model data are used to identify locations, whose current climate corresponds to other locations but with a “future climate”. However, no UDS climate impact assessment studies based on the climate analogies were found in the literature survey done for this thesis, but Denault *et al.* (2006) used measured rainfall records to detect trends which were further extrapolated to represent a future climate with respect to (constant) CF uplifts, and those were applied in UDS studies.

In the DCM approach differences between two time periods (a control period: 1971-2000 and a future period: 2071-2100) were determined using the climate model data (in the Kalmar example, RCA3 - Rossby Centre Regional Climate model, Kjellström *et al.* 2005) and then applied to another data set (in this case a measured rainfall time series). The comparison of the two time period rainfalls can focus on various rainfall properties; in the approach presented here the investigations focused on rainfall intensity. The rainfall events in the future and control periods were ranked according to their intensities, and the ratios of intensities were determined for each integer percentile of rank to define the DC factors (grouping the highest intensity rainfalls in the 90^{th} percentile, and the lowest intensity rainfalls in the 10^{th} percentile). Separate DC-factor distributions were determined for each decade within the standard 30-year climate normal and averaged to smooth out variations.

Preservation of resolution in rainfall time series

The development of $DCM_{i,s}$, in collaboration with SMHI, has improved the potential for using measured rainfall time series in modelling and analyzing climate change impacts on urban drainage. This improvement consists mainly in preserving the temporal resolution of the measured rainfall time series by applying CFs to the tipping-bucket data (i.e., the individual tips) and hence maintaining high temporal resolution, advocated by Schilling (1991) for urban runoff modelling. Similar recommendations concerning the rainfall data properties were recently presented by Willems *et al.* (2012b), pointing out the need for both temporal and spatial downscaling of climate model data required for urban hydrological impact studies. In Figure 14, the differences in both spatial and temporal resolutions of climate model data (CMD) and the data needed for urban drainage studies are shown graphically.

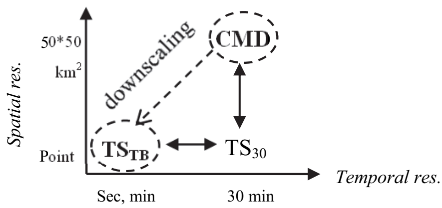

Figure 14. Differences in spatial and temporal resolutions, for the example used in Kalmar (paper I). TS_{TB} – Measured rainfall time series (tipping bucket), TS_{30} – Measured rainfall time series aggregated in 30 min intervals. CMD – climate model data (in this case RCA3, with 30 min and 50*50 km resolutions).

Spatial resolution of rainfall inputs to UDS model simulations is also important, but as considered here, it would depend on the density of the existing rain gauge network. Thus, the representativeness of historical rain data used in studies of climate change impacts on UDSs needs to be assured, as will be further discussed in the next section. As the catchment used in Kalmar was considered relatively small, one rain gauge was used for input of rainfall data (applied uniformly over the catchment). Niemczynowicz (1991) also pointed out the effect of moving storms on runoff modelling (based on results from a study in Lund), but considering the Kalmar catchment size and recommendations in the literature (ASCE 1992), such effects were considered here negligible.

Seasonal differences

Climate changes are expected to have different influence on precipitation during various seasons, e.g. in Sweden, all climate model data generally indicate wetter winters throughout the country, but drier summers in the south and wetter summers in the north (e.g., described in SOU 2007). The highest intensity rainfall events are also more likely to be found in Sweden during the summers, and generally relate to convective rainfall (e.g. Dahlström 1979; Hernebring 2006; SWWA 2011a). These aspects were considered in the development of the $DCM_{i,s}$ presented in this thesis (paper I), by dividing the climate factors into groups related to the seasons of the year.

Seasonal variations were also confirmed by comparisons of seasonal data (spring, summer, autumn, and winter). The main assumption was that the same differences detected in the climate model data (areal rainfall in this case) for the control and future periods also occur in the measured data set (tipping-bucket point rainfall). Before applying climate factors to the measured rainfall time series (a Kalmar time series 1991-2004), the time series was aggregated into 30-min intervals (to be compatible with the climate model data) and the 30-min intervals were ranked according to the rainfall intensity, and divided according to the season of the year. Then DC-factors were applied to successive 30-minute periods in the measured series, according to the rank position of each period, essentially by adjusting tipping bucket volumes. This procedure provides a new tipping bucket rainfall series, with dynamically varying volumes (from the applied DC-factors) representing the future climate (2071-2100).

Thus, the procedure used herein can be summarized as follows:

1. Climate model data (CMD) were divided into four seasons (spring, summer, autumn, and winter) to detect seasonal variations, and further ranked according to the event rainfall intensity in each of these seasonal groups.

2. Differences between the two time periods (a control period: 1971-2000 (representing Today's climate, TC), and a future period: 2071-2100 (FC)) were compared in the climate model data (CMD), and thereby change factors (corresponding to specific season and intensity levels) were determined.

$$CF_{DC\,(i,s)} = \left(\frac{i_{FC:CMD}}{i_{TC:CMD}}\right)_s$$

where $CF_{DC(i,s)}$ is the Delta Change Factor for a specific season "s" and intensity percentile "i", derived from intensity levels for the FC-Future and TC-Today's climate (i.e., the control period), for a particular season and intensity percentile; i = rainfall intensity; and, intensity levels were averaged for each selected percentile.

3. The measured time series (in this case tipping bucket data) was aggregated into 30-min intervals (to make it compatible with the climate model data) and such intervals were grouped according to the season of the year and ranked within each season according to the rainfall intensity level.

4. Delta change factors were then applied to the 30-min intervals corresponding to the same season and intensity percentile, in this case by adjusting tipping bucket volumes.

$$\left(i_{TC,Measured}\right)_{i,s} * CF_{DC(i,s)} = \left(i_{FC:Measured}\right)_{DC(i,s)}$$

where "Measured" refers to the measured rainfall time series.

4.2.2 Kalmar example of downscaling

For the summer season in the Kalmar region, the climate model scenario comparison yielded a delta change CF distribution, in which low-intensity rainfalls would possess reduced intensities in the future (2071-2100: FC3), when compared to the reference period (1971-2000: TC) designated here as today's climate (Figure 15). Contrarily, the highest intensity rainfalls would become more intense in the future, while the total rainfall depths for the summer season would decrease, as suggested by the $DCM_{i,s}$ approach. Similar general results were noted for other climate projections for Sweden (e.g. Olsson and Foster (2013) and SOU (2007)), and on a global level (IPCC (2013) and WMO (2013)).

Among the advantages of the $DCM_{i,s}$ one could list its relative simplicity and the ability to preserve the time resolution of the measured rainfall. To demonstrate the $DCM_{i,s}$ method, examples of four measured rainfall events and their transformation by the $DCM_{i,s}$ are presented in Table 14 and include: a low-intensity rainfall event (920821), a short-duration medium-to-high intensity event (940818), and two extreme rainfall events (970727 and 030729). The intensity changes are particularly pronounced for high intensity rainfall events.

The five most intense rainfall events found in the Kalmar tipping bucket time series (1991-2004) were used as inputs in model simulations of the urban drainage systems and urban green areas. The delta change factors for these rainfalls ranged from 0.65 to 1.27, during the summer season.

Table 14. Characteristics of four selected rainfall events: As measured (TC – Today's climate) and DCM-transformed ($DCM_{i,s}$), for three time periods (FC1: 2011-2040; FC2: 2041-2070; FC3: 2071-2100) and emission scenario A2 (from Paper I).

		Maximum intensity [mm/5 min]				Depth [mm]			
Date [yymmdd]	**Dur [h]**	**TC**	**FC1**	**FC2**	**FC3**	**TC**	**FC1**	**FC2**	**FC3**
920821	23.3	0.6	0.57	0.59	0.46	25.2	21.9	21.6	16.8
940818	14.6	3.0	3.3	3.4	3.6	54.8	54.9	56.8	50.8
970727	2.3	8.8	9.6	10.1	10.5	15.4	16.8	17.5	18.1
030729	7.0	12.0	13.1	13.7	14.3	93.0	99.4	104.0	104.0

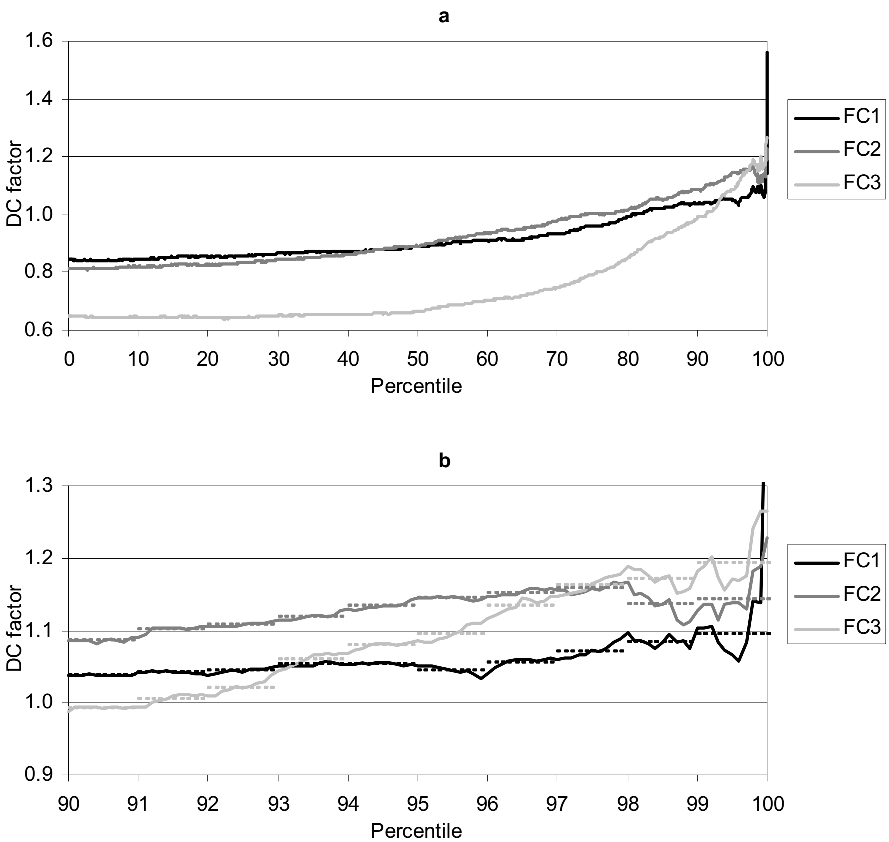

Figure 15. Percentiles of the summer $DCM_{i,s}$ distributions derived from: Today's (reference) climate (1971-2000) and three future climates (near future FC1, intermediate future FC2 and distant future FC3) developed for emission scenario A2, using the RCA3 model, with resolution 50*50 km and 30 min. Panel a: percentiles 0 – 100, Panel b: percentiles 90-100; note different y-axis scales and the factors averaged for integer percentiles (dotted lines in Panel b) (from Paper I).

When comparing the rainfall depths in the Kalmar record over 1991-2004, the observed total depth of 5743 mm changed with the DCM application into 5772 mm; application of a constant factor of 1.2 would have yielded 6137 mm. Considering just the summer season (June, July, August), the measured rainfall depths ranged from 100 to 261 mm; the DCM application yielded reduced amounts (85-236 mm), which agreed with the general climate change projections for the region (e.g., summarized in SOU 2007, with drier summers in the south of Sweden). The use of a constant factor would have increased the seasonal amounts, which would contradict the general climate change projections for this region. In Figure 16, comparisons of the two climate factor approaches (i.e., a constant CF ($CF_{CON(1.2)}$) and CFs derived by $DCM_{(i,s)}$ ($CF_{DC(i,s)}$)) are shown, highlighting some of the differences between both approaches. Analysis of the five most intense rainfalls in the Kalmar time series showed that for the summer events there was a good agreement among the uplifted rainfalls produced by the $DCM_{(i,s)}$ and the constant factor of 1.2. Only the autumn event of 1994-09-09 differed from this tendency, with the $DCM_{(i,s)}$ producing CFs as high as 1.8. This finding indicates the importance of seasonal variations in climate downscaling.

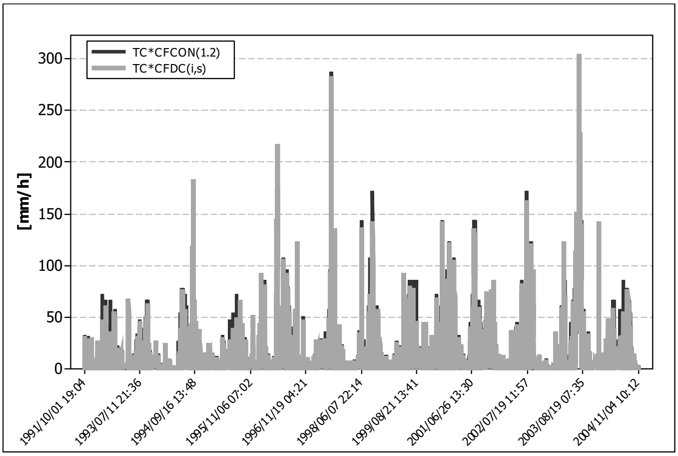

Figure 16. Kalmar rainfall time series 1991-2004, with a constant climate factor uplift ($CF_{CON1.2}$) and delta change uplifts ($CF_{DC(i,s)}$). Note that the black column is plotted only when $CF_{CON1.2}$ produces higher rainfall intensities than the $DCM_{(i,s)}$ (plotted in grey).

Variations of uplifted rainfall intensities produced by $DCM_{(i,s)}$ CFs and a constant CF of 1.2 are shown in Figure 17. The $DCM_{(i,s)}$ generally produced higher intensities than the constant $CF_{CON(1.2)}$ and these results indicate the need for further research of seasonal variations in rainfall events.

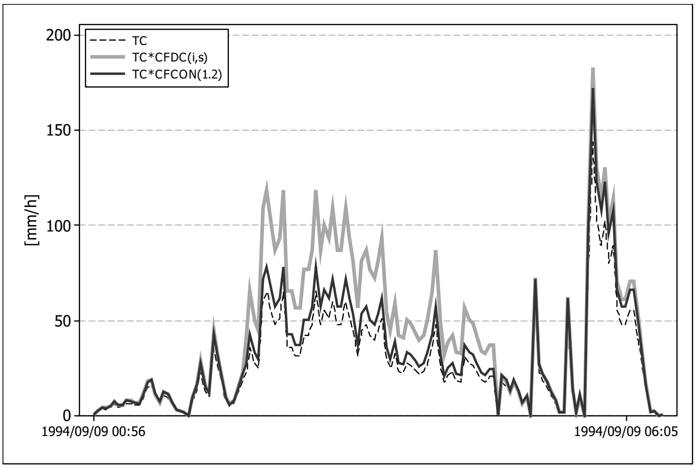

Figure 17. Autumn rainfall event 1994-09-09, adjusted by the DCM factors, as well as a constant factor of 1.2

The aspects of seasonal differences in the rainfall regime are important in water management and design of UDS. Firstly, in northern countries, the form of precipitation, whether rain or snow, is seasonally dependent and requires different management approaches, particularly with respect to water quality (e.g. US EPA 1983; Marsalek *et al.* 2008). For simulations of rainfall/runoff, seasonal differences are likely to influence the soil moisture, and particularly the initial soil moisture conditions to be selected in design storm simulations (e.g. Nishat *et al.* 2010). Further research in this area is needed, especially with the growing interest in green infrastructure (GI) and other approaches considering stormwater management with these types of solutions.

4.3 UDS response to climate change

4.3.1 Influence of future rainfall time series on UDS performance

In the Kalmar catchment study conducted with a 1D model and the rainfall time series as an input to continuous model simulations, it was found that the future rainfall (projected by the $DCM_{i,s}$) will increase the impacts on the UDS. By using the most common UDS response parameter (the number of flooded nodes), an increase in this parameter, from 15 to 38, was noted for the future climate (representing the years 2071-2100).

From continuous model simulations, it is also possible to determine the average frequency and duration of surcharging of UDS (Table 15). The frequency of surcharging also increases for the future rainfall, and for the worst node (i.e. the most frequently surcharged node, denoted as Max in Table 15), the frequency of full surcharge (water level exceeding GSE) more than doubles from 1.2 to 2.6 per year during the simulation period of 10 years. The duration of surcharging also increases in the future. At the node denoted Max in Table 14, the future surcharge duration increases by about 1 hour. The total exceedance duration also increases for the whole system. These findings indicate the potential consequences due to flooding.

Table 15. Full surcharge in UDS nodes (HGLE>GSE) and water levels exceeding the critical level (HGLE>CL: -0.5m), described by the frequency of occurrence during the 10-year period (1992-2002) and the duration, for today's climate (TC) and the future time period (FC3, representing period 2071-2100) (from paper II).

		Number of occurrences per year		Duration [h]	
Water levels in Nodes:		TC	FC3	TC	FC3
≥ GSE	Total	2.5	7.5	9.13	31.08
(full surcharge)	Max	1.2	2.6	0.73	1.80
≥ CL (-0.5 m)	Total	11.9	22.2	50.13	116.07
	Max	3.1	4.7	1.28	2.53

GSE: Ground surface elevation, CL: Critical level, Changes compared to the paper (II): only one future climate period (FC3) shown; Frequency described in number of exceedance per year instead of a 10 year period; Duration described in hours, instead of [hh:min:ss], to simplify the table and focus on the main important things in the results.

Consequences of the increased hydraulic loading of the UDS and the flooding in the urban area can be related to locations of flooded nodes, as shown in Figure 18 for the Kalmar area, where two threshold levels were used: the ground surface elevation (GSE) as well as a critical level (CL: -0.5 m). This allows a better appreciation of the system safety margins with respect to the today's climate (1971-2000) and a future climate scenario (2071-2100). The areas marked A, B, C identify locations of future flooding problems (i.e., the areas with low safety margins). In general, within this catchment, the areas with higher safety margins can be found in the upper reaches of the catchment.

The main finding: The used response parameters provided a broad and diverse assessment of the UDS hydraulic performance and identified the areas of low or high safety margins in the system. Furthermore, as also reported by others (e.g. Waters *et al.* 2003), future rainfalls increase the hydraulic overloading of UDS systems.

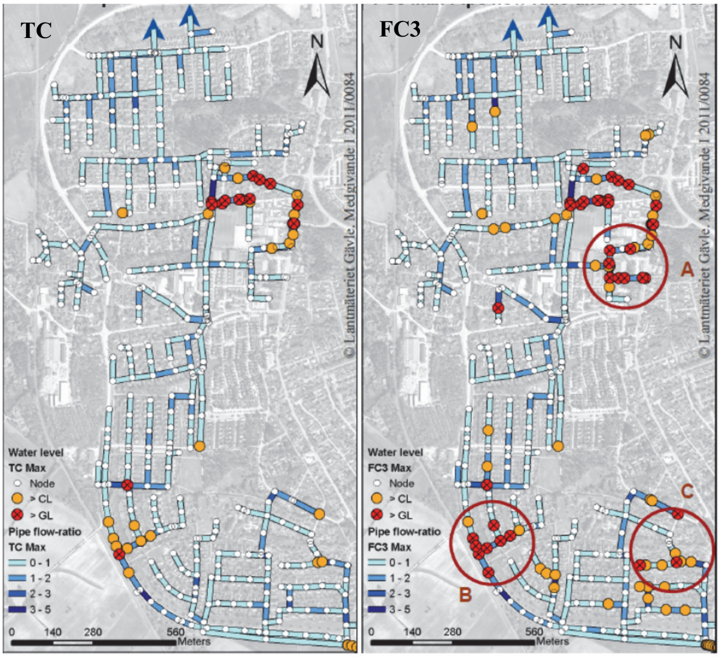

Figure 18. Consequences of the Kalmar UDS hydraulic overloading: (a) Maximum Pipe flow rate (blue), (b) flooded nodes with the ground surface elevation (GSE) exceedance (red dots) and the critical level (CL) exceedance (yellow dots), for the baseline scenario (today's climate: TC) and the future time period 2071-2100 (FC3). A, B, C marks future flooded areas (from paper II).

4.3.2 UDS performance simulated for various rainfall types and climate projection methods

In the second study of the Kalmar catchment, a refined modelling approach was used (1D/3D) in conjunction with single event rainfall inputs, facilitating reduced computation times.

Design rainfalls of Block and CDS types: current and future climates

Depending on the type of design rainfall used, the Block or CDS types tested here, the UDS responses also differed. For the peak flow at the outlet, these differences were not as marked as for the number of flooded nodes in the system (Table 16), pointing out the importance of relevant choices of response parameters. The Design Block rainfall yielded a relatively low response compared to that caused by the CDS rainfall, which agrees with the earlier research (e.g. Arnell 1982) indicating that even though the CDS rainfalls are commonly recommended and used for UDS design in Sweden (SWWA 2011a), they represent the "worst case" approach ascribing maximum rainfall intensities for various durations to a single event rainfall (Alferi *et al.* 2008). After applying climate factors to design rainfalls, the differences in response further increase (Tables 16 and 17).

Table 16. Number of flooded nodes and peak discharges (at the main outlet) simulated for various rainfall inputs (from paper III); total number of nodes in the Kalmar catchment: 440.

Rainfall type	T* [y]	Peak discharge [m^3/s]			Number of flooded nodes [-]		
		TC	$CF_{CON(1.2)}$	$CF_{DC(i,s)}$	TC	$CF_{CON(1.2)}$	$CF_{DC(i,s)}$
Block	2	1.51	1.65		1	2	
Block	5	1.75	1.90		3	17	
Block	10	1.94	2.08		22	45	
Block	100	2.34	2.37		185	215	
CDS	2	1.65	1.80		2	7	
CDS	5	1.89	2.04		15	28	
CDS	10	2.06	2.17		35	61	
CDS	100	2.35	2.41		202	246	
1994-09-09	2	1.66	1.82	2.11	2	9	40
1996-06-19	2	1.57	1.72	1.69	2	7	6
1997-07-27	5	1.84	1.99	2.03	18	35	32
2002-07-24	2	1.61	1.77	1.82	3	10	8
2003-07-29	100	2.36	2.43	2.48	194	241	253

*T – Return period, defined for design storms; for measured rainfall events, an equivalent return period was derived from IDF curves.

Generally CDS storms cause higher runoff than a Block rainfall (e.g. Arnell 1982, Alferi *et al.* 2008). On the other hand, model simulations with simple Block rainfall inputs yield information on critical rainfall durations for different locations within the catchment and may be therefore useful for determining whether the sub-catchments (and different parts of the sewer system) will be surcharged by short, high-intensity rainfall events, or by longer rainfalls with high total rainfall depths (Table 18).

Table 17. Kalmar UDS response to various rainfall inputs: (a) Flooded nodes with flow spilling onto the surface (the hydraulic grade line elevation, HGLE>GSE), (b) Nodes at which HGLE exceeds critical levels (HGLE>CL), and (c) Flooded areas for three threshold levels (L) above the ground (the total number of nodes = 440, the total drainage area = 22.7 km^2 (from paper III)).

			Percent of nodes affected (%)		Flooded area (%)		
Rainfall	**T* [y]**	**CF****	**GSE:0.0m**	**CL:-0.5m**	**L:0.05m**	**L:0.10m**	**L:0.15m**
Block	2	-	0.2	2.5	0.0	0.0	0.0
Block	5	-	0.7	8.2	0.3	0.0	0.0
Block	10	-	5.0	17.7	0.9	0.2	0.1
Block	100	-	42.0	68.9	20.2	6.8	2.5
Block	2	1.2	0.5	4.1	0.1	0.0	0.0
Block	5	1.2	3.9	16.4	0.7	0.1	0.0
Block	10	1.2	10.2	24.8	2.5	0.4	0.2
Block	100	1.2	48.9	75.7	28.7	12.5	6.4
CDS	2	-	0.5	3.6	0.1	0.0	0.0
CDS	5	-	3.4	14.8	0.5	0.1	0.0
CDS	10	-	8.0	22.7	1.8	0.3	0.1
CDS	100	-	45.9	73.6	24.9	10.5	5.1
CDS	2	1.2	1.6	10.7	0.3	0.0	0.0
CDS	5	1.2	6.4	20.2	0.1	0.3	0.1
CDS	10	1.2	13.9	33.4	4.5	0.8	0.3
CDS	100	1.2	55.9	78.4	33.3	15.6	9.6
1994-09-09	2	-	0.5	3.9	0.1	0.0	0.0
1996-06-19	2	-	0.5	4.3	0.0	0.0	0.0
1997-07-27	5	-	4.1	15.2	0.5	0.1	0.0
2002-07-24	2	-	0.7	4.5	0.1	0.0	0.0
2003-07-29	100	-	44.1	72.0	27.3	12.2	6.4
1994-09-09	2	1.2	2.0	9.3	0.3	0.0	0.0
1996-06-19	2	1.2	1.6	8.0	0.2	0.0	0.0
1997-07-27	5	1.2	8.0	22.0	1.2	0.2	0.1
2002-07-24	2	1.2	2.3	11.8	0.4	0.1	0.0
2003-07-29	100	1.2	54.8	78.4	35.7	17.2	11.4
1994-09-09	2	DC	9.1	23.0	2.4	0.4	0.2
1996-06-19	2	DC	1.4	8.4	0.2	0.0	0.0
1997-07-27	5	DC	7.3	21.6	1.1	0.2	0.1
2002-07-24	2	DC	1.8	10.7	0.3	0.0	0.0
2003-07-29	100	DC	57.5	80.5	37.8	18.6	12.4

*T – Return period, defined for design storms and equivalent for measured rainfalls.

** CF: 1.2 = $CF_{CON(1.2)}$ CF: DC = $CF_{DC(i,s)}$ ($DCM_{i,s}$ based on paper I).

Table 18. Critical durations in flooded nodes, related to the number of flooded manholes/nodes as a result of running Block rainfalls of different durations.

Block Dur	5	10	15	20	30	40	50	60	90	120 (min)	Tot (nodes)
Block 2y	1										1
Block 5y	1	1			1						3
Block 10y	1	4	5	6	5	1					22
Block 100y	5	29	44	40	34	23	0	7	2	1	185

The differences between the Block and CDS types of rainfall (using a paired nodes statistical evaluation) showed that the water levels in this system were 0.14-0.19 m higher for a CDS rainfall input, than for the Block type of rainfall. The corresponding numbers of flooded nodes were 60% higher (35 vs 22 nodes) for CDS. After applying a climate factor (CF 1.2, $CF_{CON(1.2)}$) the difference in the response for the CDS and Block rainfalls increased further, although the relative difference in the number of flooded nodes declined, by 35% (61 vs 45 nodes). Thus, depending on the safety margin in the system, the difference in actual numbers of flooded nodes can vary by more than the difference in maximum water levels. The added climate factor ($CF_{CON(1.2)}$) will increase the maximum water levels more for the CDS rainfall compared with the Block rainfall. Future CDS produced 0.27-0.33 m higher levels than today´s CDS rainfall and for the Block hyetograph, water levels in the future were 0.20-0.25 m higher. The difference between Block and CDS was less than the difference due to added climate factor of 1.2.

In Figure 19 it can also be seen that Block rainfalls generate water level responses lower than those for CDS rainfalls (showed for a 10-year return period), and after applying the climate factor ($CF_{CON(1.2)}$), such differences further increased. Thus, it is important that designers are aware of possible differences in water levels caused by rainfall inputs, particularly when accounting for climate change by applying climate factors to rainfall inputs and studying the resulting impacts on UDSs.

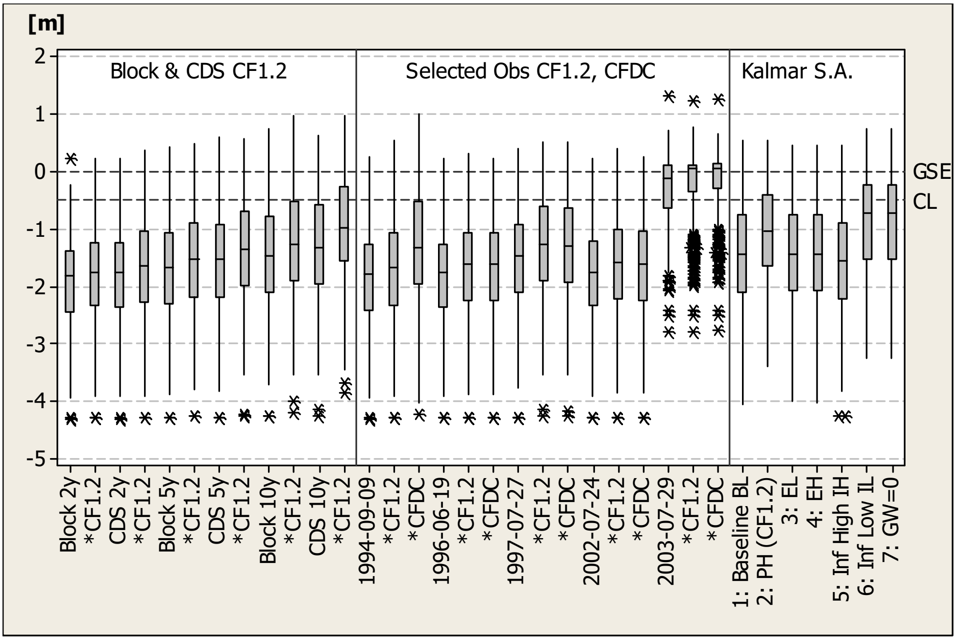

Figure 19. Maximum water levels at UDS nodes, related to the Ground surface elevation (GSE) and a critical level (CL= -0.5m), from studies in the Kalmar catchment: (a) Block and CDS (paper III); (b) Measured rainfalls, with two climate factors applied (CF1.2=$CF_{CON(1.2)}$ and CFDC=$CF_{DC(i,s)}$ (paper III); (c) Sensitivity Study (S.A): BL – Baseline; Precipitation high (PH); Low and High Evapotranspiration (EL, EH); High and Low infiltration capacity (IH and IL), and high groundwater level (GW=0)), (paper VII).

Design rainfalls (Block and CDS) and selected rainfalls from a time series

It is commonly assumed that the response of the urban drainage system to a design rainfall of a given return period is similar to that caused by flooding event of the same return period. The return periods of different duration segments in the measured rainfall, however, correspond to a variety of return periods, rather than to one specific value as in the case of the design storm. Comparison of the five selected measured rainfalls with design rainfalls of the same (assigned) return period produced very similar flooding responses, in terms of the number of affected nodes, peak flows at the outlet (Table 16 and 17) and the maximum flooded area (Table 17).

When comparing specific water levels produced by the measured rainfalls with a 2-year return period (rainfalls 1994-09-09, 1996-06-19, and 2002-07-24) to those produced by the design storms, the lowest responses were produced by block rainfalls, and the maximum water level responses from CDS rainfall were higher or equal to those of the measured storms (Figure 19). Thus the results indicate that measured rainfalls may yield responses similar to those of CDS events for similar return periods. This is probably due to similar hyetograph shapes of CDS and measured events, with peaks clearly rising above the constant values of the Block rainfalls.

Selected measured rainfalls uplifted with two different types of climate factors

Runoff simulations for measured rainfalls showed that applications of a constant climate factor ($CF_{CON(1.2)}$) or of those obtained from the delta change approach ($CF_{DC(i,s)}$) produced similar results with respect to the maximum water levels at nodes, except for the event of 1994-09-09, for which the seasonal differences in DC (autumn vs summer) are clearly shown (Figure 19). The numbers of affected nodes for different climate factors and rainfalls were shown in Tables 16 and 17. The DC factor uplifts have a more varying impact pattern and especially the event 1994-09-09 stands out. This was also discussed in an earlier section (4.2.2), pointing out differences in rainfall intensities and uplift CFs for different seasons. The results presented here indicate the consequences of rainfall uplifting in the form of hydraulic response in the UDS, during both the autumn event 1994-09-09 and the summer event 2003-07-29 which had higher maximum CFs than the constant CF of 1.2 ($CF_{CON(1.2)}$).

Some caution needs to be taken when deciding on using either a constant climate factor or Delta Change factors, as there are limitations in both approaches. Adding a constant uplift factor focuses on the changes in intensity but will increase both the intensity and the volume of the rainfall. A constant factor will increase both as much, which may not agree with seasonal changes of the volume. For the delta change approach (paper I) both changes in intensity and total volume for each season are taken into account when applying diversified factors to the entire time series.

Finally, the water levels at UDS nodes for various scenarios and climate factors were summarized from the thesis papers and are shown in Figure 19. For the most severe rainfall inputs (100-y Block and CDS design storms and the measured event 2003-07-29), even before accounting for climate change, the areas with lowest safety margins of the Kalmar UDS are already flooded (about 45% of all nodes) and affected by elevated water levels in the system (about 70% of all nodes) (Table 17).

These findings (section 4.3.2), can be summarized as follows: (a) the type of rainfall influences the UDS hydraulic response (for both today and future climate), (b) the choice of rainfalls may also enhance the evaluation possibilities (e.g. Block rainfalls in a series, identifying differences in critical durations in the catchment); and (c) choice of climate factor method may also influence the UDS hydraulic response, indicating the influence of the maximum factors as well as their seasonal variations.

Sensitivity study in the Kalmar catchment

From the sensitivity analyses for Kalmar catchment UDS responses were also examined, as presented in Table 19 and Figure 19.

Table 19. Number of surcharged pipes and nodes, and pipe flow rates derived from runoff simulations in Kalmar catchment for various scenarios (from paper VII). Kalmar catchment: 440 nodes.

	Number of nodes/pipes:	Max water levels		Pipe flow rate
Catchment	Run	≥ GSE	≥ CL: -0.5 m	Q/Q_{full} ≥1
Kalmar	1: Baseline, BL	22 (5%)	80 (18%)	115 (26%)
	2: Prec. High, PH ($CF_{CON(1.2)}$)	40 (9%)	137 (31%)	152 (35%)
	3: ET Low, EL	22 (5%)	80 (18%)	116 (26%)
	4: ET High, EH	22 (5%)	80 (18%)	115 (26%)
	5: Infiltration High, IH	15 (3%)	72 (16%)	98 (22%)
	6: Infiltration low, IL	57 (13%)	168 (38%)	176 (40%)
	7: Groundwater High, GW=0	57 (13%)	168 (38%)	176 (40%)

WL – Water levels relative to the Ground, GSE – Ground surface elevation, and CL – critical level (set at -0.5 m below ground in this case).

A highly permeable soil (e.g., scenario 5 IH) reduces hydraulic loading on the UDS, and for such cases, adaptation measures based on enhanced infiltration should be feasible. For areas with less permeable soils and/or high groundwater levels (e.g., scenarios 6 IL and 7 GW=0), other climate change adaptation measures would be needed, essentially providing additional storage (e.g., in stormwater ponds, or bioretention facilities with engineered soils) and runoff detention (e.g., in vegetated strips) (Marsalek *et al.* 2008). The evapotranspiration scenarios (3, and 4) did not influence the UDS hydraulic performance, but it is understandable due to the short simulation period used. For longer simulation times, evapotranspiration components have potential to influence the soil moisture conditions (the initial conditions for rainfall-runoff modelling).

The scenario with soils of low permeability, underlain by bedrock (6 IL) and the scenario with high groundwater table (7 GW=0), showed similar UDS impacts, which were higher than those corresponding to the scenario with a climate factor ($CF_{CON(1.2)}$) applied (Precipitation High, PH-Kalmar in Figure 19). Note that combinations of the scenarios tested are possible; e.g., the occurrence of high groundwater table (7 GW=0) and uplifted rainfall (2 PH) could be also considered and would yield increased impacts on the UDS and the resulting consequences.

Water balance components simulated for the above scenarios broadly varied (Figure 20), with the main influence exerted by soil permeability. For baseline conditions and sandy soil with relatively high infiltration capacity, the water balance is dominated by infiltration (80-85%) and moderate runoff (18-15%). For zero infiltration capacity in pervious (green area) catchment elements (i.e., shallow bedrock or groundwater table extending to the surface), there is no infiltration, runoff represents about 50% of water input and the remaining water temporarily ponds on the surface. Contributions of green areas to the volume of runoff conveyed by the UDS was about 2-3% for the

Baseline scenario 1, and about 0 for scenario 5 (high Infiltration – sandy soil), and more than 30% for scenarios 6 (bedrock) and 7 (high groundwater level). These findings indicate that green areas with good infiltration capacity function as effective sinks of rainwater and can be used that way in climate change adaptation measures. However, in areas with tight soils, or shallow bedrock, or high groundwater tables, with the latter condition being potentially caused by a hydraulic overload of infiltration surfaces (leading to groundwater mounding), these measures become ineffective and runoff storage gains on importance.

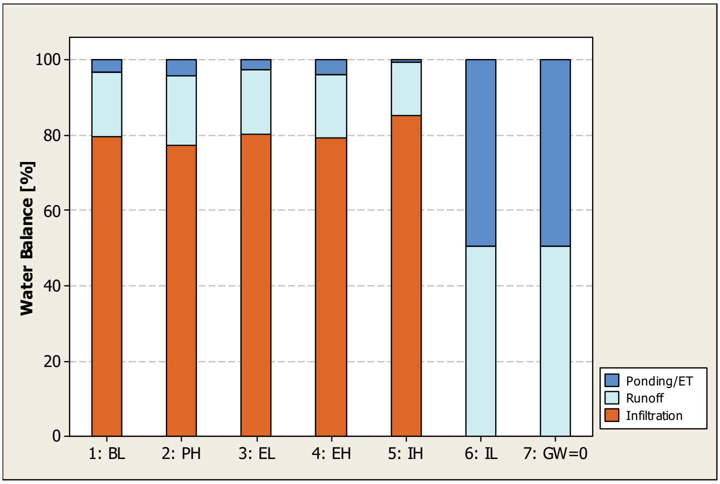

Figure 20. Sensitivity analysis of the Kalmar catchment water balance, 1: Baseline scenario (BL), 2: Precipitation High (PH), 3: ET Low (EL), 4: ET High (EH), 5: High infiltration capacity (sandy soil) (IH), 6: Low infiltration capacity (bedrock) (IL), and 7: Groundwater table reaching to the surface (GW=0) (based on results from paper VII, with addition of scenario 7). Water balance losses described as: Ponding/ET.

Even larger increases can be observed for soils with low, or zero infiltration capacity (e.g., shallow soils, or bedrock – scenario 6). Perhaps the worst conditions increasing the climate change impacts on UDS are combinations of soils with low infiltration capacities and high groundwater tables. In terms of hydrological response, such combinations are analogous to high imperviousness of the catchment. Groundwater tables vary seasonally and their high elevations in spring and fall may coincide with uplifted precipitation, during the same period, projected for a large part of Sweden. Joint occurrences of high water tables and increased precipitation would further contribute to higher runoff volumes and peaks in future climates.

Results of the sensitivity analysis performed in paper VII provided information on the hydrology of green/pervious areas, which was used in a later paper on green urban areas and on-site stormwater management, and green roofs. The importance of the infiltration capacity of the soil (or soil type) was highlighted. Evapotranspiration /Evaporation abstractions during short rainfall events were not influential, although in a longer perspective, they could influence greatly the soil moisture initial conditions before rainfall occurs.

Urban catchment/UDS simulation software

As also pointed out by others, future climatic conditions related to the urban stormwater management need to be addressed by computer simulations of future climate change scenarios by urban runoff models (e.g., Borris *et al.* 2013). Any of the current well-established advanced models (including the DHI models used in this thesis) is capable of simulating the generation of urban stormwater runoff for broadly varying conditions, with a high level of certainty (Zoppou 2001). Model software used in all the modelling work in this thesis was based on the DHI models: Mouse-MikeUrban (1D), MikeShe (3D), and Mouse coupled with MikeShe (1D/3D). The software choices reflected the nature of the modelled systems and were in agreement with recommendations in the literature. In general, other types of software similar to DHI models (SWWM, InfoWorks, and others) could have been also used.

To reduce potential bias introduced into the climate change impact analysis, the interpretation of modelling results did not focus on magnitudes of simulated quantities, but rather on the assessment of sensitivity of the catchment and UDS responses to climatic influences. Such an approach was in agreement with that adopted by Nemec and Schaake (1982) and later by others (Willems *et al.* 2012b), and focused on differences between model simulations, and the description of such differences by the response parameters defined in the preceding section. Therefore, the model results were deemed adequate for comparative purposes, and for illustrating the methodology developed in the thesis. Hence, this methodology and comparative results should provide guidance for assessing the climate change impacts on other urban catchments and UDSs.

In paper II, a 1D modelling approach was used for the continuous model simulations with a rainfall time series. This type of approach does not readily identify the flooding of nodes, because the model allows the hydraulic pressure grade line to exceed the ground surface elevation, without water spillage on the catchment, as also discussed by others (e.g. Nie *et al.* 2009; Leandro *et al.* 2009). As a result, the responses in the UDS may be overestimated, because the spillage also works as a safety release limiting the pressure build up in the UDS. In paper III a refined model set up for the Kalmar area was used (1D/3D), thus enabling the modelling of more extreme rainfall events, as well as urban area flooding.

4.4 Influence of runoff from green urban areas on UDS response

4.4.1 Urban green areas

The early designs of urban drainage and of UDS focused on the role of impervious areas, which appeared to be practical in densely developed urban areas with high imperviousness. However, there is a growing interest in urban green infrastructures and utilization of green areas for sustainable stormwater management (e.g. Ellis 2013). Hence, runoff contributions from green areas were simulated and analyzed in a fair detail. It was noted that the green, fully pervious sub-areas have a large potential to act as storage, or sinks, of urban runoff generated on such sub-areas, or diverted onto them from impervious sub-areas. For analyzing such processes, it is important to address soil infiltration and moisture storage capacity, and their dynamic state, further influenced by groundwater tables. In this thesis, indications of such issues are given in paper VII, and paper IV.

Modelling runoff from green urban areas is challenging for a number of reasons, including e.g., presence of vegetation, soil compaction, non-homogeneity of urban soils, and presence of sewers and buildings foundations (e.g. Fletcher *et al.* 2012). Also soil infiltration processes influenced by macropore flows are important, as they in general increase the overall permeability of the soil and tend to reduce overland runoff generation (Weiler and Naef 2003). For modelling urban green areas influence on urban drainage systems (comprising both above and below ground components), the occurrence of overland runoff and its contribution to the catchment runoff is of higher importance regarding flooding than the infiltration and soil moisture processes, even though these processes are closely related and soil moisture conditions influence e.g., the infiltration into sewers, which is a relatively slow process. A modelling approach with Richards Equation, as used e.g. in MikeShe, provides detailed results concerning the vertical and horizontal distributions of soil moisture, but without reflecting horizontal flows in the soil, which might occur in the vicinity of sewer pipes or in soil layers of different permeability. Thus, the issues of soil non-homogeneity and horizontal flows below green areas are among the topics requiring further study.

Modelling runoff generated by single events, such as design storms, requires the specification of initial soil moisture conditions (Nishat *et al.* 2010, Camici *et al.* 2011, Watt and Marsalek 2013). Essentially, dry conditions provide additional water storage in the top soil layer and thereby contribute to lower runoff, as used in innovative stormwater management (Marsalek and Schreier 2009). Contrarily, wet conditions assume that this storage is partly or completely filled, and hence higher runoff depth result. While theoretically, a number of numerical values could be assumed, for practical reasons, this choice is usually limited to two cases: wet or dry, as suggested by e.g. Deletic (2001) and Villarreal *et al.* (2004).

Runoff contributions of green areas are described in this section with respect to: (a) water balance and (b) factors influencing water balance, when modelling a green urban test plot (10 x 20 m). These issues are of a particular interest in connection with on-site implementation of stormwater management (Marsalek and Schreier 2009) in today's and future climates by infiltrating/storing the incoming rainwater or runoff diverted from nearby impervious areas. Additionally, green roof potential compensation for increases in future rainfall depths are also indicated by exemplifying differences related to some Swedish regions (from south to north).

4.4.2 Factors influencing the runoff component of water balance

Among the influential factors studied, soil permeability, described here by the soil type, was the most influential parameter in runoff simulations, followed by the initial soil moisture conditions. Water balance components simulated for three common Swedish soil types (fine, intermediate, and coarse tills) and CDS rainfalls with return periods ranging from 2 to 100 years are shown in Figure 21.

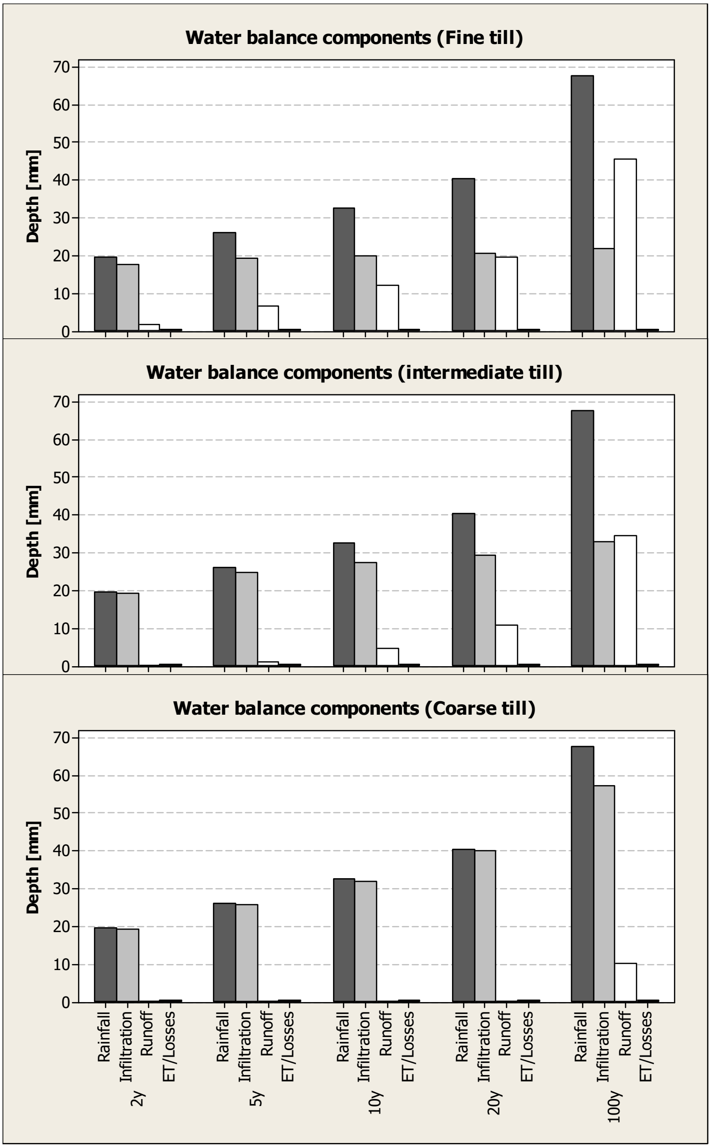

Figure 21. Water balance components (Rainfall, Infiltration, Runoff, ET – Evapotranspiration/ Evaporation and Losses) generated by CDS rainfalls with return periods 2-100 years, on green test plots with three soil types and dry initial moisture conditions (from paper IV).

As demonstrated in Figure 21, for fairly permeable coarse tills, there is practically no runoff, with the exception of the 100-year CDS, when runoff volume represents about 15% of incoming rainfall. Hence, such soils infiltrate rainwater and could be used for shorter return periods events considered in minor drainage design (2-10 years) and in stormwater management (return periods < 1 year) to infiltrate additional volumes of runoff projected for future climates, or diverted from adjacent impervious areas. The last consideration also applies to intermediate tills, which started to produce some runoff (13.4% of rainwater) for the return period of 10 years, and for a 100-y CDS event, 51% of incoming rainwater was converted into runoff. Finally, fine tills produced even greater relative volumes of runoff, with a 5-y CDS producing the runoff volume equivalent to 25% of rainwater and the corresponding proportion for the 100-y CDS being 68%. Hence, fine tills would be still capable of coping with rainfall/runoff increases in future climates, but their capacity for accepting additional runoff from potentially large adjacent areas would be somewhat limited.

Soil moisture represents a hydrological abstraction which is used up by infiltrating water, and can be used advantageously in stormwater management. If that storage is full at the onset of storm event, as described by wet initial soil moisture conditions, the rainfall input will generate more runoff, as demonstrated in Figure 22 for intermediate till. This runoff increment is just 2 mm for a 2-y CDS, and ranges from 6 to 9 mm, for return periods ranging from 5 to 100 years. Obviously for short return periods, there is an insufficient supply of infiltrating water to completely fill the soil moisture storage. Similar differences were also found for a fine till soil.

The influence of climate with uplifted rainfalls ($CF_{CON(1.2)}$) on runoff generation is the largest for storms with long return periods (100-year), and can be described by a runoff volume increment of 13 mm, for both wet and dry initial soil moisture conditions and intermediate till (Figure 22). For shorter return periods of rainfall, the runoff depth increment was 3-7 mm, again, for dry or wet initial soil moisture conditions. These reported increases in runoff are comparable to the increased rainfall depth, due to climate change, by 4, 5, 6, 8, and 14 mm (with $CF_{CON(1.2)}$), for rainfalls of 2, 5, 10, 20, and 100-year return period, respectively. The increased runoff amount for an Intermediate till soil is for a rainfall of 2-year return period: 0-3 mm, 5-year return period: 3-4 mm, 10 years: 5 mm, 20-year: 6-7 mm (Figure 22).

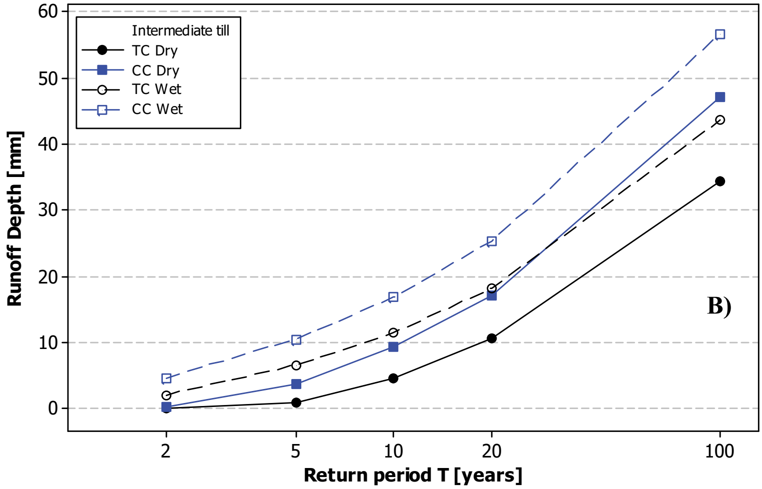

Figure 22. Green plot runoff depths for storm events with various return periods, initial soil moisture conditions (dry or wet), a constant uplift climate factor applied ($CF_{CON1.2}$), and intermediate till soil type (from paper IV).

Green area soils

Concerning the soils tested, they represent fairly common soil types found in Sweden, with soil permeability increasing from the fine till to intermediate and coarse tills. These results indicate the importance of green areas (and in fact, of the whole green infrastructure) for stormwater management, because they can act as sinks of surface runoff for a broad range of storms. Hence, this potential of green areas to serve as adaptation measures for future climate rainfall/runoff should be recognized already when planning catchment development layouts and focusing on diversion of runoff from impervious onto green areas in the existing catchment requiring adaptation for future uplifted rainfalls.

For the three soil types tested, fine to coarse tills, the study results indicated that the choice of initial moisture conditions, wet or dry, was particularly influential for less permeable soils (i.e., a fine till), in which the infiltration process is slower and wet conditions are likely to persist longer. On the other hand, a more permeable soil (like a coarse till studied here) drains quickly and is less likely to stay wet for a longer period of time. Large differences were found when comparing low permeability soils (Fine till), with wet soil moisture conditions, and high permeability soils (Coarse till), with dry initial soil moisture conditions (paper IV).

4.4.2 Potential use of green roofs in adaptation to future climates

Hydrologic behaviour of green areas in controlling surface runoff can be used in adaptation of urban catchments and their drainage to future climates with uplifted precipitation. Examples of such applications are diversions of runoff from impervious elements onto urban green areas and green roofs, which besides runoff control offer a multitude of additional benefits as well (Mentens *et al.* 2006; Berndtsson 2010). Green roofs mimic the essential hydrologic properties of urban green areas and their numerous benefits were summarised e.g., by Berndtsson (2010) who reported that green roofs reduce and attenuate stormwater runoff and thereby lower the risk of urban flooding; contribute to maintaining the local water balance in a state similar to the natural one; reduce noise and air pollution; conserve energy by enhancing roof insulation; reduce export of waste heat by roof runoff; mitigate the urban heat island impacts; and, create new ecosystems. Berndtsson (2010) also pointed out two factors which influence the green roof water detention/retention capacity and runoff dynamics:

- green roof characteristics (e.g. layers, materials, soil thickness, soil type, vegetation cover, type of vegetation, slope and length of roof, roof exposure to sunshine, roof age); and
- weather conditions (e.g. the duration of the antecedent dry period, season, air temperatures, wind characteristics, humidity, and rainfall events intensity and duration).

The second point is addressed in the discussion that follows. From a Swedish climate perspective, the green roof performance in reducing runoff needs to be related to different seasons of the year, which were defined in Table 20, on the basis of the literature data, as very cold, cold, mild, warm, and very warm. In the same table, the extent of green roofs in urban catchments was considered at three levels, representing 5, 10 and 15% of the total catchment area. Potential seasonal reductions in roof runoff volume were then listed in table columns and ranged from 0.8% (i.e., reduction during a very cold season for green roofs applied to 5% of the catchment area) to 21.3% (during a very warm season and green roofs covering 25% of the catchment area).

Data in Table 20 indicate that the highest potential for roof runoff reduction occurs during the warm and very warm seasons; hydrologic benefits of green roofs during very cold and cold seasons are relatively small (almost negligible). A similar analysis of green roof hydrologic benefits was applied in future climate scenarios addressing four seasons (winter, spring, summer and autumn) in the year of 2100. Climate projections for four Swedish geographical regions, showed that during summer, when green roofs are most effective, only the Norbotten region (in Northern Sweden) displayed higher precipitation (by 4.1%), but in other regions, precipitation declined (paper VI). On the other hand, precipitation increased in all the regions in winter, when green roofs are the least effective. A summary of seasonal hydrologic performance of green roofs in the four Swedish regions is presented in Table 21.

Table 20. Potential seasonal reductions of roof runoff volumes by green roofs, extending over 5-25% of the urban catchment area (modified from paper VI).

Green roof area	**Rainfall depth reduction***, in different climatic conditions				
In percentage of the catchment area	**Very Cold[1] (15%)**	**Cold[2] (30%)**	**Mild[3] (50%)**	**Warm[4] (75%)**	**Very Warm[5] (85%)**
5%	0.8	1.5	2.5	3.8	4.3
10%	1.5	3.0	5.0	7.5	8.5
15%	2.3	4.5	7.5	11.3	12.8
25%	3.8	7.5	12.5	18.8	21.3

*Total roof runoff reduction from an experimental green roof unit (%); **Very Cold** [1]: *15%.* values for Dec-Feb, Southern Sweden (Bengtsson *et al.* (2005) (19-32%) and the Middle region of UK (Stovin *et al.* 2012) (5-6%). **Cold** [2]: *30%.* values for Dec-Feb, Germany (Mentens *et al.* 2006), about 33%. **Mild** [3]: *50%.* values for Sep-Nov, Mar-May, from Germany (Mentens *et al.* 2006), and Southern Sweden (Bengtsson *et al.* 2005), about 55% on average (very variable values). **Warm** [4] : *75%.* values for Jun-Aug from Southern Sweden (Bengtsson *et al.* 2005), and Germany (Mentens *et al.* 2006), average about 75%. **Very Warm** [5] : *85%.* summer conditions (Bengtsson *et al.* 2005; Mentens *et al.* 2006; Stovin *et al.* 2012), about 85%.

Data in Table 21 indicate that green roofs would be most effective in Norrbotten, where the summer increase of precipitation in the future climate could be successfully controlled by green roofs covering just 5% of the catchments. By extending the GR coverage to 15%, the potential roof runoff reductions in all the regions would be 16-73% and 16-43% for spring and autumn climatic changes, respectively. Considerations of future warmer temperatures would further enhance green roofs potential, because of shifts in seasons from cold towards warm and the concomitant improvements in green roof effectiveness.

These results indicate potential usefulness of green roofs, as an adaptation measure, as was also pointed out by others (e.g., Berndtsson 2010 and references in Table 20). This study, however, focused on the seasonal potential reductions, rather than annual reductions referred to in most of the aforementioned references. Hydrological behaviour of green roofs is also affected by rainfall characteristics, such as intensity, duration, and the total rainfall depth, as well as antecedent soil moisture conditions reflecting antecedent precipitation and temperature, and ET. Among the rainfall characteristics, the total rainfall depth imposes a significant limit on the green roof performance (e.g., Teemusk and Mander 2007; Hilten *et al.* 2008). After the green roof storage capacity has been exhausted, additional rainfall is converted to runoff. Thus, the effectiveness of green roofs may differ for specific events, but the general results still give general indications of the green roofs potential to reduce rainfall depths, for the whole of Sweden. Seasonal variations affect the green roof performance, but in a future warmer climate (as is suggested by IPCC 2013), the evapotranspiration potential and effectiveness of green roofs is likely to improve, even in the northern parts of Sweden. Nevertheless, more research is needed to fully answer the related research questions.

Table 21. Potential seasonal reductions of roof runoff volumes by applications of green roofs (GRs) in a future climate (year 2100), for Green roofs covering 5-15% of the catchment area, and four Swedish regions: Gävleborg, Norrbotten, Skåne, and Värmland (modified from paper VI).

		Rainfall reduction (%) related to future climate changed precipitation			
		Winter	Spring	Summer	Autumn
Skåne		*(Very cold-Cold)**	*(Mild)**	*(very Warm)**	*(Mild)**
	CC Prec incr (%)	*49*	*14*	*-27*	*18*
	5% GR	2.3	17.5	-	14.2
	10% GR	4.6	35.0	-	28.4
	15% GR	6.8	52.4	-	42.6
Gävleborg		*(very cold)**	*(Cold-Mild)**	*(Warm-very Warm)**	*(Cold-Mild)**
	CC Prec incr (%)	*41*	*8*	*-2*	*23*
	5% GR	1.8	24.4	-	8.7
	10% GR	3.7	48.8	-	17.4
	15% GR	5.5	73.2	-	26.1
Värmland		*(very cold)**	*(Cold-Mild)**	*(Warm-very Warm)**	*(Cold-Mild)**
	CC Prec incr (%)	*46*	*32*	*-21*	*20*
	5% GR	1.6	6.2	-	10.3
	10% GR	3.2	12.4	-	20.5
	15% GR	4.9	18.6	-	30.8
Norrbotten		*(no red.)*	*(Cold)**	*(Warm)**	*(Cold)**
	CC Prec incr (%)	*54*	*28*	*4*	*28*
	5% GR	-	5.4	91.5	5.4
	10% GR	-	10.9	100.0	10.7
	15% GR	-	16.3	100.0	16.1

*possible reduction rates from Table 20.

5 Conclusions

Within the context of the thesis presented and the appended papers, a number of conclusions concerning the four thesis objectives can be drawn:

- The Safety Margin Approach (SMA), presented in this thesis and consisting in the use of UDS hydraulic performance parameters related to critical threshold levels, offers a number of advantages in the analysis of the catchment and its UDS vulnerability to hydraulic impacts of climate change, including highlighting and identifying safety margins within the UDS, with respect to hydraulic performance.

- The SMA approach also improves potential identification of those parts of the catchment, which are characterized by a high runoff generation potential (in terms of volumes and peak flows), and therefore may produce high runoff inflows to the UDS.

- By developing and applying Delta Change Method (DCM) climate factors ($DCM_{i,s}$) to measured rainfall data, the temporal rainfall resolution in the measured time series is preserved. Where the measured data meet the requirements on high temporal and spatial resolution, such qualities are maintained in the uplifted rainfall data, and make such data well applicable in urban runoff modelling. However, a further examination of measured data may be required with respect to their quality control and representativeness concerning the capture of high-intensity events with return periods similar to those employed in drainage design.

- Delta change method ($DCM_{i,s}$) can also be used to highlight seasonal differences in the uplifted climate factors. With a growing interest in urban green areas, and their hydrological processes and potential to reduce runoff, the need to account for seasonal aspects of runoff generation is also increasing. The hydrological processes in urban green areas are relatively slow (e.g., dynamics of soil moisture conditions, groundwater levels, and evapotranspiration/evaporation) and their study and modelling require rainfall time series as inputs, in order to study these processes in a sufficient detail. Where single rainfall modelling is applied, initial soil moisture conditions need to be specified.

- The choices of the UDS modelling input rainfall data, in the form of design storms, strongly affect the simulated response. The Block-type design rainfalls of various durations improve identification of critical conditions in the UDS and identify whether short high-intensity rainfall events, or longer duration rainfalls with a greater total rain depth are critical for various parts of the UDS, because the response of different UDS parts is related to specific "critical storm durations". On the other hand, design rainfall inputs of the Chicago Design Storm (CDS) type yield greater UDS responses, partly because of the CDS peaky hyetograph shape and partly because the event represents, in most climates, the "worst case" scenario, and consequently, the identification of areas/sections with low safety margins is very marked.

- The modelling of urban green areas and choices of rainfall inputs also influence their runoff response, and such influences were studied in this thesis in a fair detail. Climate and seasonal influences on the soil moisture conditions, as well as groundwater levels, will change the response of the catchment/UDS system to the rainfall input data scenarios.

- While climate change with uplifted rainfalls tends to increase runoff contributions from all urban surfaces, strategic application of runoff controls in the form green infrastructure and runoff diversion onto green areas may counterbalance such increases, and even lead to reduced runoff inflows into the UDS. Thus, sustainable stormwater management offers adaptation opportunities, where technically feasible.

- Green roofs mimic most hydrologic features of green areas and can be applied in runoff control in most urban areas, without the usual restrictions applicable to many other BMPs (e.g., land availability, permeable soils, etc.). A simple analysis applied in this thesis showed that green roofs, if applied over sufficiently large areas, could control a large part of future runoff volume increases, for the whole of Sweden. However, further research is needed on the green roof effectiveness and design in cold climate, and on potential uptake of this measure in urban communities.

- The above summarized findings provide a general guidance for climate change adaptation measures: in areas with tight soils, provision of storage will be an important option, but in areas with well-drained soils, increasing hydrologic abstractions by redirecting runoff onto green and pervious areas will be an attractive and inexpensive alternative to storage.

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Paper I

Applying Climate Model Precipitation scenarios for urban hydrological assessment: A case study in Kalmar city, Sweden

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Applying climate model precipitation scenarios for urban hydrological assessment: A case study in Kalmar City, Sweden

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ABSTRACT

There is growing interest in the impact of climate change on urban hydrological processes. Such assessment may be based on the precipitation output from climate models. To date, the model resolution in both time and space has been too low for proper assessment, but at least in time the resolution of available model output is approaching urban scales. In this paper, 30-min precipitation from a model grid box covering Kalmar City, Sweden, is compared with high-resolution (tipping-bucket) observations from a gauge in Kalmar. The model is found to overestimate the frequency of low rainfall intensities, and therefore the total volume, but reasonably well reproduce the highest intensities. Adapting climate model data to urban drainage applications can be done in several ways but a popular way is the so-called Delta Change (DC) 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 DC factors (DCFs) are related to the rainfall intensity level. This is achieved by calculating changes in the probability distribution of rainfall intensities and modelling the DCFs as a function of percentile. Applying this method in Kalmar indicated that in summer and autumn, high intensities will increase by 20–60% by year 2100, whereas low intensities remain stable or decrease. In winter and spring, generally all intensity levels increase similarly. The results were transferred to the observed time series by varying the volume of the tipping bucket to reflect the estimated intensity changes on a 30-min time scale. In an evaluation of the transformed data at a higher 5-min resolution, effects on the intensity distribution as well as single precipitation events were demonstrated. In particular, qualitatively different changes in peak intensity and total volume are attainable, which is required in light of expected future changes of the precipitation process and a step forward as compared with simpler DC approaches. Using the DC transformed data as input in urban drainage simulations for a catchment in Kalmar indicated an increase of the number of surface floods by 20–45% during this century.

1. Introduction

Hydrological changes and increased frequency of heavy precipitation events are very likely to occur in the 21st century, as a result of higher global mean temperature (IPCC, 2007). This will have great impact on urban environment and infrastructure. Especially high-intensity rain will cause problems such as flooding because of limitations in the existing urban drainage systems. 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 summer precipitation will 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).

In order to assess impacts in urban drainage systems with model simulations, precipitation input data of a high temporal

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resolution is needed (e.g. Schilling, 1991). A preliminary study of the urban drainage system in Kalmar, Sweden, showed for example that the number of floods was about 30% lower when using a 30-min time step in the input data representing high intensity rainfall events, compared to using a 5-min step (Olofsson, 2007; Berggren, 2007). The future changes of high intensities are of key importance as these rainfalls will have great impact on the urban drainage systems. To assess the future rainfall properties relevant for urban hydrological processes, two main strategies may be identified. One strategy is to use historical data to estimate trends of key rainfall properties. It should be emphasized that the detection of trends in short-term, local precipitation extremes is often very difficult due to short data series as well as natural variations. Pagliara et al. (1998) found that short-duration annual maxima in Tuscany, Italy, have increased since the mid-20th century, whereas the increase was less pronounced for long-duration extremes. Arnbjerg-Nielsen (2006) found that the maximum 10-min intensity has a statistically significant increasing trend in eastern Denmark. This kind of trends may then be projected or extrapolated into the future, as done by e.g. Denault et al. (2006) for an urban catchment in British Columbia, Canada. Using the Storm Water Management Model (SWMM) with future rainfall intensities estimated from the extrapolated trends resulted in an increase in peak design discharges by more than 100% until year 2050.

The second main strategy is to use output from general circulation models (GCMs), applied to simulate the response to various greenhouse gas scenarios. As these operate on a coarse spatial resolution (typically ~3°), downscaling is required for regional assessment and two main strategies exist. In dynamical downscaling, a regional climate model (RCM) is nested inside the GCM to increase the resolution to typically ~0.5° (e.g. Giorgi and Mearns, 1999; Kjellström et al., 2005). Statistical downscaling, on the other hand, is based on statistical relationships between GCM output and regional observations (e.g. Hewitson and Crane, 1996; Rummukainen, 1997). The regional resolution reached by this downscaling is however still too coarse for urban hydrological assessment and therefore either further or other types of downscaling is required in this context. One approach is to use climate model output as a basis to modify parameters of stochastic weather generators and point rainfall models (e.g. Schreider et al., 2000; Onof et al., 2002). Most commonly, however, the output is used to quantify the percentage change in rainfall intensity between today and some future time, known as delta change (DC; e.g. Hay et al., 2000; Schreider et al., 2000; Andréasson et al., 2004). Typically, a multiplicative delta change factor (DCF) is estimated by comparing climate model output representing today's and future climate, respectively. Then the factor is applied to rescale an observed rainfall time series for subsequent use in some type of hydrological modelling.

In an urban hydrological context, Niemczynowicz (1989) in a pioneering study applied delta change to Intensity-Duration-Frequency (IDF) curves in Lund, Sweden, and used the resulting intensities as input in SWMM modelling. The DCFs were varied between +10% and +30%, in line with general estimates from GCM output available at the time, and it was found that the percentage change in runoff volumes became even higher. More recently, a similar study with overall similar results was performed in Ontario, Canada (Waters et al., 2003). Schreider et al. (2000), based on output from different GCMs, found a 20% maximum increase in summer rainfall in Australia until year 2070. Results from hydrological modelling indicated only a minor effect on urban flood damage. Semadeni-Davies et al. (2005), in a joint study of the effects on urban drainage related to both climate change and increased urbanisation in Helsingborg, Sweden, used a version of the DC method with different factors for low and high rainfall intensities (drizzle and storm), respectively. The monthly DCFs were found to vary widely between a 50% decrease and a 500% increase for the period 2071–2100, implying that both season and intensity level need to be taken into account. Grum et al. (2006) made an effort to include the difference in spatial resolution between the climate model output and the observations by complementing delta change with an observed relationship between point value extremes and spatially averaged extremes, respectively. Generally the results indicated that in the period 2071–2100, extreme events will occur at least twice as frequently as in the recent past, i.e. a certain intensity will have an approximately halved return period. It may be remarked that this kind of point-areal analysis requires a dense network of gauges with a high temporal resolution, something that is seldom available in practice.

The objective of this study is to refine the DC procedure, i.e. to apply future changes in precipitation on a historical rainfall time series, using DCFs reflecting both the variation between seasons and the changes of different intensity levels. The latter is achieved by employing a version of the DC method which is based on comparison between different percentiles in the frequency distribution of precipitation intensities, representing today's climate and future climates, respectively. Thus, instead of single DCFs, a distribution of factors covering the entire range from low to high intensity levels is derived. This provides a more complete description of the anticipated future change in rainfall intensities than in previous applications of the delta change method, and further makes it possible to modify observations in a more detailed way. A method to transfer the results to an observed tipping bucket rainfall time series is proposed, in which the bucket volume is considered variable.

The intended application of the DC method developed is urban hydrological assessment and therefore the city of Kalmar, south-eastern Sweden, is used as a study area. Climate projections derived from the regional climate model RCA3 are used. Model precipitation in the period 1961–2100 with a 30-min time resolution from three grid boxes in the Kalmar region are extracted and analysed. DCF distributions for three different future time periods are estimated and the future changes transferred to an observed high-resolution time series. This procedure and the resulting series will enable further assessment of climate change impacts on the urban drainage system in the area.

2. Precipitation data and evaluation for today's climate

The precipitation data sets used in the study are (1) high-resolution observations for the period 1991–2004 from a gauge in Kalmar, Sweden, and (2) output from the RCA3 climate model for the period 1961–2100 from the grid box covering Kalmar (and two adjacent boxes). In a comparative

Fig. 1. The location of Kalmar in south-eastern Sweden.

evaluation, the realism of the modelled precipitation is assessed.

2.1. Study area and data bases

The study area is the city of Kalmar in south-eastern Sweden (Fig. 1), which was selected mainly because an urban drainage and sewer model (MOUSE) was set-up for a residential area in the city and directly available for simulations. This area has a population of 3000 and a contributing catchment area of 54 ha, of which 20 ha is impervious. Observed rainfall data from Kalmar consist of a 13-year time series (1991–2004) of rainfall observations from a tipping-bucket gauge in Kalmar with a volume resolution of 0.2 mm. This data set is described in Hernebring (2006), which includes a general quality assessment such as comparison with daily, seasonal and annual accumulations from a nearby gauge. An analysis of cumulative deviations from the mean (e.g. Buishand, 1982) revealed no apparent inhomogeneity in the data set. The average annual precipitation in Kalmar as obtained from daily observations is ~500 mm. The highest short-term intensities are caused by convective storms during summer, therefore the analyses and model applications in this study are generally focused on this season.

Climate model data consist of 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. Two different so-called SRES emission scenarios were run, A2 and B2. The scenarios differ with respect to the expected future global development in economical, social and technological terms. Very generally, A2 assumes a high future anthropogenic impact on climate whereas in B2 the impact is assumed to be more moderate (Nakićenović et al., 2000). A detailed description and evaluation of the experiment is given in Kjellström et al. (2005).

For this study, a 140-year time series of 30-min precipitation was extracted from the RCA3 output, for the grid box covering Kalmar. One issue, however, when using climate model output concerns the variability between model grid boxes. As a grid box covers 2500 km^2, its output mainly represents the dominant geographical characteristics of the box, which are more or less different from the characteristics of a particular location within the box. For example, the city of Kalmar is located on the Swedish east coast, i.e. on the border between land and sea. The grid box covering Kalmar has a land fraction of 70% and a mean altitude of 78 m.a.s.l., but if the Kalmar precipitation is strongly influenced by the sea, it may be that the neighbouring grid box in the east (land fraction 13%, mean altitude 8 m.a.s.l.) is more relevant. To study this issue, RCA3 data from the neighbouring grid boxes east and west (96%, 169 m.a.s.l.) of the Kalmar box were also extracted and analysed.

Within the total 140-year period, four 30-year sub-periods were selected to represent different climate perspectives: (1) today's climate (TC), 1971–2000; (2) near-future climate (FC1), 2011–2040; (3) intermediate-future climate (FC2), 2041–2070; (4) distant-future climate (FC3), 2071–2100.

2.2. Comparative evaluation

Comparing climate model output representing present climate (from a climate change scenario experiment) with observations during a limited time period is very uncertain for a number of reasons. On a very general level, models are always simplifications and observations always have errors, and this axiom is perhaps especially true in the case of climate models and precipitation observations. More specifically, the climate is characterised by low-frequency oscillations or cycles on decadal time scales. As climate models are not tuned to reproduce these oscillations it may well be that they are out of phase in this respect, i.e. they cannot be expected to reproduce e.g. “dry” or “wet” decades. These uncertainties exist for comparisons at low resolutions (regions, seasons) and are exacerbated at the high resolutions considered here (grid box, 30 min). A further complicating factor is the discrepancy in spatial scale between the 50×50 km RCA3 output and the point observations. Thus, in essentially all aspects the point observations are expected to differ from RCA3 output from the same period. Even so, by comparing the data sets the realism of the RCA3 output may be assessed, even if on a very general level (e.g. qualitative reproduction of seasonal cycles), which provides some indications concerning the applicability of RCM output at its highest resolution for local assessment.

In Table 1, some key statistical properties of the observed data, aggregated into 30-min intervals, are compared with the corresponding statistics in the climate model data: average 30-min intensity, maximum 30-min intensity, standard deviation and percentage of dry 30-min periods. The comparison is made for the 10-year period in which the period selected to represent today's climate overlap with the available observations, i.e. 1991–2000. The comparison is made on a seasonal basis with summer defined as Jun–Aug, autumn as Sep–Nov, winter as Dec–Feb and spring as Mar–May. It should be emphasized that the only variable that can be strictly compared between observations and gridded climate model output is the average 30-min intensity, as over a long period of time this should be the same in a point as in the surrounding area.

If first looking at the difference between scenarios A2 and B2, the average value is higher in A2 for three of the seasons and the maximum value is higher in B2 for three of the

Table 1
Comparison of descriptive statistics between tipping-bucket observations (OBS) and RCA3 Kalmar grid box precipitation for emission scenarios A2 and B2 in today's climate.

	Summer				Autumn				Winter				Spring			
	Avg	Max	Std	PD	Avg	Max	Std	PD	Avg	Max	Std	PD	Avg	Max	Std	PD
OBS	0.030	15.0	0.33	96	0.031	12.2	0.20	94	0.013	3.6	0.09	97	0.022	5.8	0.14	95
A2	0.054	3.3	0.16	52	0.058	1.9	0.14	49	0.051	1.8	0.12	48	0.044	1.7	0.11	55
B2	0.053	3.2	0.15	51	0.061	2.5	0.14	48	0.049	2.2	0.11	49	0.042	1.9	0.11	57

Variables: average 30-min intensity (Avg; mm/30 min), maximum 30-min intensity (Max; mm/30 min), standard deviation (Std; mm/30 min) and percentage of dry 30-min periods (PD; %).

seasons. The standard deviation and the percentage of dry periods are both very similar. In total the differences between A2 and B2 are small and may well be attributed to statistical scatter rather than reflecting some actual systematic differences.

The differences between the gauge data and the climate model data are more clear. Concerning average precipitation, this is substantially overestimated in the model. It should however be noted that tipping-bucket gauges generally underestimate the long-term volume, and indeed Hernebring (2006) found that the daily gauge in Kalmar recorded ~25% more precipitation than did the tipping-bucket gauge. This indicates that the actually observed volume is higher, but still RCA3 overestimates this amount by ~50% in summer, autumn and spring. In winter the overestimation reaches ~200%, which may at least partly be related to inaccurate gauge recordings during periods with snowfall. The observed pattern with higher average values in summer and autumn than in winter and spring is qualitatively reproduced in the model.

The percentage of dry 30-min periods (PD) is ~95% in the observations but only ~50% 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 RCA model has been found to overestimate the frequency of low and moderate intensities (e.g. Räisänen et al., 2004; Kjellström et al., 2005; Carlsson et al., 2006). Thus model inaccuracy is most probably contributing to the underestimated frequency of dry periods as well as the overestimation of average intensity. In the model data PD is somewhat higher in summer and spring than in autumn and winter. This may reflect the more frequent frontal passages during the latter seasons, but this tendency is not clear in the observations.

Concerning maximum intensity, in summer it is ~3 mm in the RCA3 data 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 rainfall total is reduced when considering an area surrounding the point location. Different types of ARFs exist (storm-centred or location-fixed) and in a strict sense ARF analysis requires a gauge network and considerations about e.g. network density, rainfall-producing mechanisms and spatial extensions. As no proper gauge-network-based ARF analysis is available for the study region the performance of RCA3 in this context cannot be assessed, but we propose that by using ARF values from the literature a rough indication on the realism of the maxima in the RCA3 model can be obtained. Thus, the use of the ARF concept here is based on the assumption that generalised ARFs are meaningful also for relating local maxima from climate models to observed point maxima.

In NERC (1975), the recommended ARF for a duration of 30 min and an area of 3000 km^2 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 around twice the RCA3 maximum. The second to fourth highest observed maxima are however all ~10 mm, corresponding to an areal value of ~4 mm which is reasonably close to 3 mm (the second to fourth highest maxima in the RCA3 data are also ~3 mm). A general reason for the underestimated extremes is most probably limitations in the physical description of rainfall generation in the RCA3 model.

Also in autumn the observed maximum (12.2 mm) is clearly extreme. The second to fourth highest maxima are ~7 mm, with ARF = 0.41 corresponding to an areal value of ~3 mm which is reasonably close to the modelled maxima. In spring the observed maximum is not as extreme and the relationship between observed and modelled maxima is well in line with the ARF. In winter, the observed maximum is 3.6 mm and modelled maximum ~2 mm, which implies an ARF ≈ 0.6. This is qualitatively reasonable as maxima in this season are generally produced by frontal passages, which are characterized by a smaller difference between the point value maximum and the spatially averaged maximum, respectively (e.g. Allen and DeGaetano, 2005).

Concerning the observed standard deviation, this exhibits a clear seasonal pattern, reflecting the highly variable convectively induced summer precipitation as well as the evenly distributed predominantly stratiform winter precipitation. The RCA3 data well describes the variability in winter, which is in line with the large-scale processes involved, but as expected the variability is underestimated as small-scale convective systems cannot be resolved in the model. The observed seasonal pattern is however qualitatively reproduced, albeit with small differences between the seasons.

Concerning the issue of grid box variability, the results from the surrounding grid boxes in the east and in the west were somewhat ambiguous. In terms of average intensity and percentage of dry periods, model data from the eastern grid box are systematically slightly closer to the observations than data from the grid box centred over Kalmar. Thus, in this respect, the overall maritime character of the rainfall regime in Kalmar appears better represented by the sea-dominated neighbouring grid box. Maximum values are, however, generally better represented in the land-dominated grid box in the west, implying that high intensities in Kalmar are associated with generating mechanisms of a more inland character. Thus, the grid box centred over Kalmar conceivably represents a mixture of the maritime and inland rainfall regimes, and therefore we focus on data from this box in the following.

Overall the RCA3 model results appear to reasonably well reproduce the features of the observed precipitation. It is clear that the model generates too much rainfall, most probably due to an overestimated frequency of low intensities. It may be remarked that this inaccuracy is likely to have little significance in the context of urban flooding. More significant are the maximum 30-min intensities, and these appear overall realistic in the model generated data.

3. Future precipitation changes in climate model output

The RCA3 precipitation is analysed to assess the character of the future changes, as represented in the 140-year transient climate simulation. A refined version of the delta change method is described, after which results are presented, in detail for the summer season and more briefly for the other seasons. The reason for focusing on summer is that virtually all the highest rainfall intensities occur in this season. Only the results for the grid box centred over Kalmar City are presented, but it may be mentioned that the results from the neighbouring grid boxes are overall similar.

3.1. Methodology: delta change (DC)

As briefly reviewed in the Introduction, for urban hydrological purposes the delta change (DC) method has been applied in different ways. Most investigations have focused on the highest intensities, e.g. as expressed in IDF-curves, and their expected future increase. In this study, however, the final objective is storm water modelling using as input not design storms but continuous rainfall time series. Thus we need to consider not only the highest intensities but all intensity levels, i.e. the entire probability distribution of rainfall intensities. For a certain climate perspective, the distribution of delta change factors (DCFs) is estimated as the ratio between percentiles in the future intensity distribution and percentiles in today's distribution (for the same season and emission scenario). The DCF distribution is finally applied to an observed time series (Section 4 below). This approach represents a general methodology where a certain data set is modified based on the corresponding percentiles in another data set. A well-known example is the unbiasing of climate model ensembles in Wood et al. (2002), where percentiles in modeled and observed climatology distributions are used to adjust long-range hydrological forecasts.

For each of the four climate perspectives (TC, FC1, FC2, FC3; Section 2.1), percentiles of the intensity probability distributions were thus calculated to estimate the DCF distributions. For each perspective, percentiles were calculated separately for each of the three 10-year periods within the total 30-year period (first, middle, last). This was done in order to obtain different realizations of the distribution. The percentiles were calculated with a resolution of 0.1, i.e. representing probabilities of non-exceedance in the range 0, 0.1, 0.2…99.8, 99.9, 100. To obtain a smooth and stable estimate of the DCF distributions for a certain future climate perspective, an averaging procedure was used. In this procedure, DCF distributions were estimated for all nine possible combinations of future and present 10-year periods. These nine distributions were averaged to obtain the final DCF distribution of each climate perspective.

In the calculation of DCF distributions, the lowest intensities were omitted. As indicated in Table 1 as well as in previous evaluations, the RCA3 precipitation is characterized by an overestimated frequency of very low intensities, leading to an overestimation of the average 30-min intensity and an underestimation of the percentage of dry 30-min periods. Different strategies can be used to omit low intensities, one being to use a cut-off intensity threshold below which all values are replaced by zero. If using a fixed threshold in the DCF analysis, however, the DCF for the minimum intensity (0th percentile) will after the cut-off be forced to unity which is an artificial and undesirable restriction. Instead we consider a fixed proportion of the intensity probability distribution. This proportion was estimated based on the comparative evaluation in Section 2.2. Originally the RCA3 output overestimated the average intensity by approximately a factor two (Table 1). To obtain the same average intensity as in the observations, the RCA3 intensity distributions representing today's climate had to be truncated at approximately the 85th percentile. Thus the average intensity of the 15% highest values in the RCA3 data is approximately equal to the observed average intensity. Therefore the DCF analysis in the following is performed for intensity distributions truncated at the 85th percentile (the remaining 15% generally corresponds to ~3000 intensity values for a certain 10-year period and season). For climate perspective TC, this approach roughly corresponds to a cut-off threshold of ~0.2 mm/30 min, which is also the volume resolution of the tipping-bucket gauge used in this study.

3.2. DCF distributions: summer

Table 2 shows the future change of the rainfall statistics used in Table 1. In scenario A2 there is a clear trend towards less total summer precipitation in the future, with only ~80% of today's volume in FC3 (2071–2100). The maximum intensity, however, is expected to increase up to 4–5 mm/30 min. The percentage of dry periods is nearly constant with only a slight increase in FC3. In scenario B2 change is less systematic, but overall most variables remain fairly constant during the future climate periods. The only notable change is a pronounced increase in the maximum value, from 3.2 today up to 5–6 mm/30 min in the future.

Fig. 2 shows the percentiles for summer season, climate perspectives TC (1971–2000) and FC3 (2071–2100), emission scenario A2. The percentiles have been averaged over the three 10-year periods in each of the two perspectives. Below the 90th percentile, the TC curve is located above the FC3 curve, implying that intensities up to 90% probability of non-exceedance will decrease between TC and FC3. For the lowest intensities considered, the decrease is ~35%. At the 90th percentile the curves cross, and for higher percentiles TC is below FC3, i.e. the highest intensities will increase. For the very highest intensities, in the range 99–100%, the increase is 15–25%. The pattern in Fig. 2 reflects a change towards lower total summer precipitation due to a decreased intensity during periods of light rainfall (drizzle). On the other hand, the intensity during periods of heavy and very heavy rainfall will increase, possibly owing to intensified convective activity.

Table 2
Descriptive statistics of RCA3 Kalmar grid box precipitation for emission scenarios A2 and B2 in the different climate perspectives.

	TC				FC1				FC2				FC3			
	Avg	Max	Std	PD	Avg	Max	Std	PD	Avg	Max	Std	PD	Avg	Max	Std	PD
A2	0.054	3.3	0.16	52	0.050	5.0	0.16	52	0.050	3.7	0.16	53	0.042	3.6	0.15	56
B2	0.053	3.2	0.15	51	0.050	5.8	0.16	52	0.056	4.6	0.17	50	0.052	4.6	0.17	51

Variables: see Table 1.

Fig. 3a shows the summer DCF distributions for all three future climate perspectives, emission scenario A2. Concerning FC3, in line with the results in Fig. 2, the DCF is <1 below the 90th percentile and >1 above it, ranging from ~0.65 to ~1.25. Concerning FC1 and FC2, the change is principally similar to FC3 but less pronounced. The DCFs are in the range ~0.8–1.15 and the transition from DCFs <1 to >1 takes place at the 70th–80th percentile.

As indicated in Fig. 3a, although not clearly visible, there is a pronounced scatter in the DCFs for the very highest percentiles. Thus the division into 10-year periods with subsequent averaging is not sufficient to fully smooth out the DCF fluctuations associated with extreme intensities. The remaining fluctuations are likely to have contributions from both statistical noise and from a climate change signal, but the relative proportions are unknown. The fluctuations complicate the transfer of the DCF distribution to an observed rainfall time series, as similar but slightly different very high observed intensities may be rescaled using substantially different DCFs that varies up and down in an inconsistent way. It is hardly realistic to represent the climate change signal in such a detailed way, where a certain DCF is applied to just a few observed values. To further smooth the DCF distributions, these were therefore averaged over integer percentiles. Fig. 3b shows the result for the percentile interval 90–100% in Fig. 3a. The averages overall well describe the different curves, without excessively smoothing out the variations. The very highest DCFs do become somewhat lower this way, but on the other hand more robust and credible.

The summer DCF distributions for both emission scenarios using integer percentiles are shown in Fig. 4. For scenario A2 (Fig. 4a), the DCFs for the highest percent of intensities, DCF_{99}, are 1.10 for FC1, 1.14 for FC2 and 1.19 for FC3. Concerning scenario B2, the overall pattern of the DCF curves is similar to A2, but the decrease of low intensities is less pronounced and the increase of high intensities is more pronounced. The values of DCF_{99} are 1.19, 1.23 and 1.29, respectively. In total, the results suggest a future increase in extreme summer rainfall intensities by 20–30% in the Kalmar region, accompanied by a decrease of low intensities.

3.3. DCF distributions: autumn, winter and spring

DCF-distributions for seasons other than summer are shown in Fig. 5 (emission scenario A2 only). Autumn (Fig. 5a) is particularly characterized by a pronounced increase of the extreme intensities. The value of DCF_{99} ranges from 1.28 for FC1 to 1.63 for FC3. As mentioned in Section 2.2, a typical autumn extreme intensity in today's climate is ~7 mm/30 min. A DCF of 1.6 implies an increase of this typical autumn extreme to ~11 mm/30 min by the end of this century. This may be compared with the situation in summer. Today's typical extreme is ~10 mm/30 min and the corresponding DCF_{99} for FC3 is ~1.2, which gives a future typical summer extreme of ~12 mm/30 min. This suggests that the autumn extremes may approach the magnitude of the summer extremes in the future climate, as represented in the RCA3 data. In autumn also low intensities increase, although not at all as pronounced as the highest intensities. For FC1 the DCF is very close to 1 up to approximately percentile 85, i.e. lower intensities remain unchanged, and for FC2 and FC3 the DCF for low intensities is ~1.1.

For scenario B2 (not shown) the pattern is qualitatively similar to A2, but the increase of both low and high intensities is not as pronounced as in A2. DCF_{99} is ~1.2 for both FC1 and FC2, and 1.45 for FC3.

The winter DCF distributions (Fig. 5b) indicate a similar change of all intensity levels for both FC1 and FC2, and the pattern is similar for emission scenario B2. The average DCF over all percentiles, $\overline{DCF}$, for FC1 is ~1.2 in both A2 and B2. For FC2, the value of $\overline{DCF}$ is 1.35 in A2 and 1.28 in B2. For FC3, the

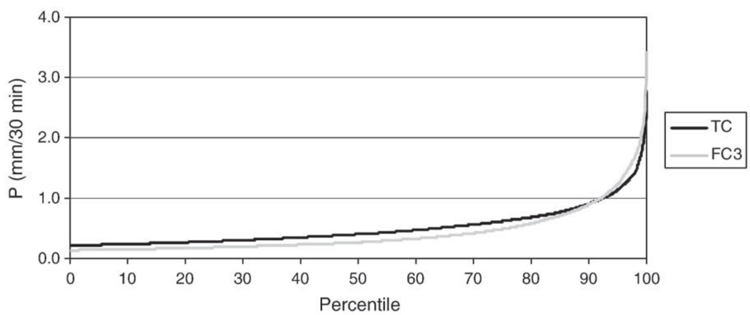

Fig. 2. Percentiles of the summer precipitation distribution in the RCA3 output for climate perspectives TC and FC3, respectively, emission scenario A2.

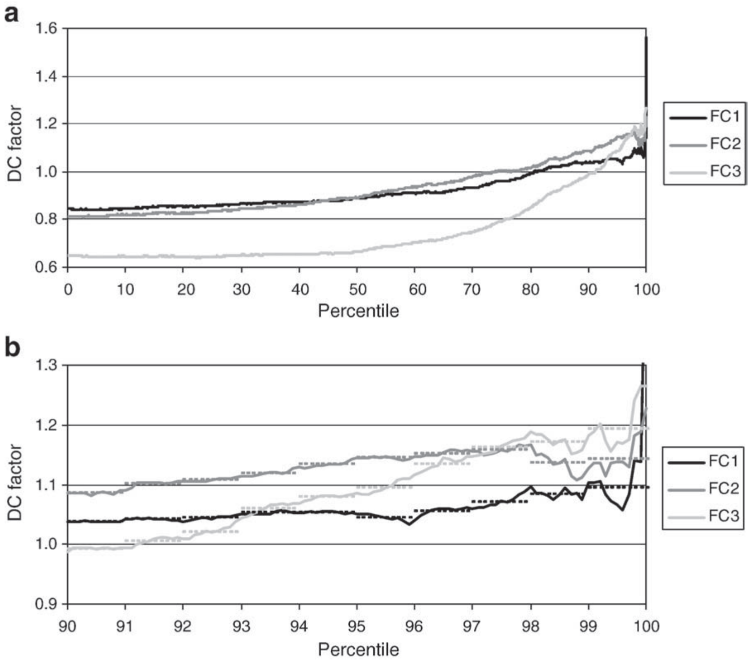

Fig. 3. Percentiles 0–100 (a) and 90–100 (b) of the summer DCF distributions, emission scenario A2 (solid lines). Note the different scales on the *y*-axis. In (b), the distributions are averaged over integer percentiles (dotted lines).

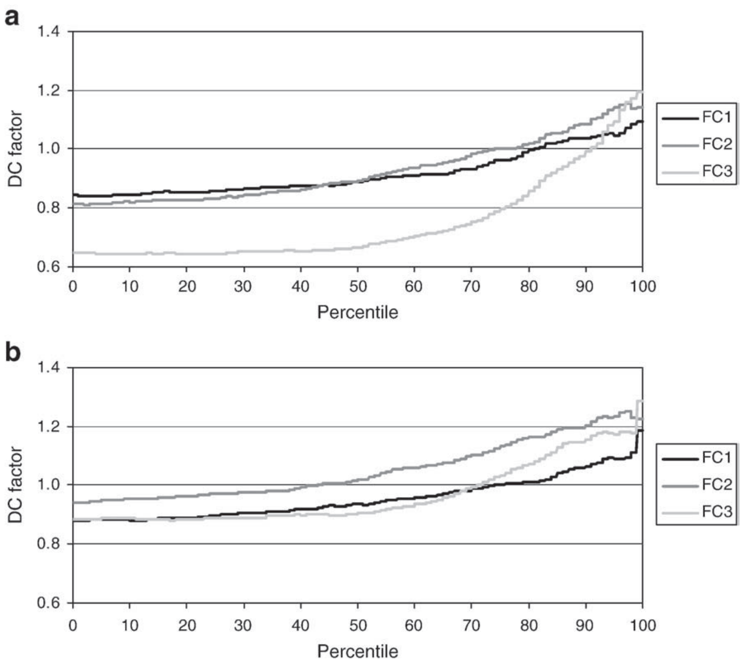

Fig. 4. Integer percentiles of the summer DCF distributions for emission scenarios A2 (a) and B2 (b).

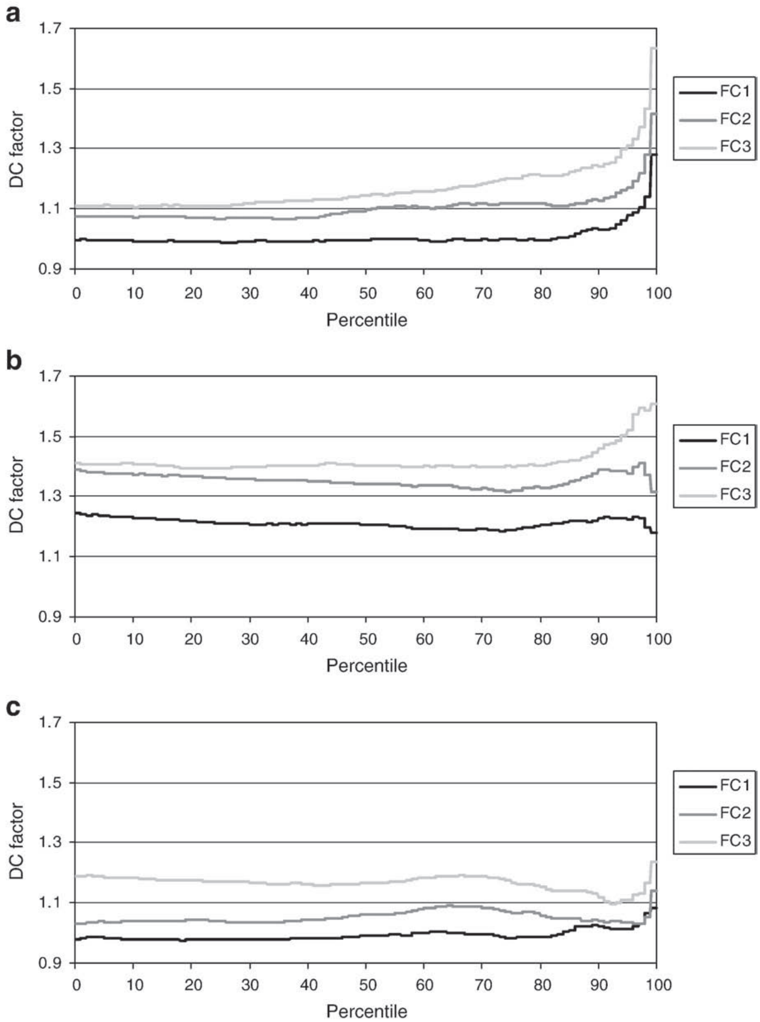

Fig. 5. Integer percentiles of the DCF distributions for autumn (a), winter (b) and spring (c), emission scenario A2.

highest intensities increase more than the lower ones, with DCF_{99} being 1.61 in A2 and 1.51 in B2. The DCFs for lower intensities are 1.3–1.4.

The situation in spring is qualitatively similar to that in winter, with a similar increase over the entire percentile range. In A2 (Fig. 5c), $\overline{DCF}$ ranges from 1.00 for FC1 to 1.17 for FC3. In B2, $\overline{DCF}$ for FC1 and FC3 is ~1.1, whereas for FC2 the value is 1.15. The DCFs for the highest intensities are fluctuating but still DCF_{99} exhibits a systematic future increase, from 1.08 to 1.24 in A2 and from 1.12 to 1.20 in B2.

4. Assessment of future point precipitation

Climate model data are in the form of continuous time series with a fixed time step but high-resolution observations are specified by "tipping times". Therefore the DC results cannot be directly transferred to the observations. A method to transfer the DC results was developed, which is described and evaluated for summer precipitation in the following sections.

4.1. DCF application to observations

The DCF distributions for FC1, FC2, FC3 were applied to the observed time series after first having (1) extracted the summer season data from the entire time series and (2) aggregated the tipping-bucket recordings into 30-min intensities. From the observed 30-min values, percentiles of the distribution were calculated. Then, for each 30-min value, its corresponding percentile was identified and the value

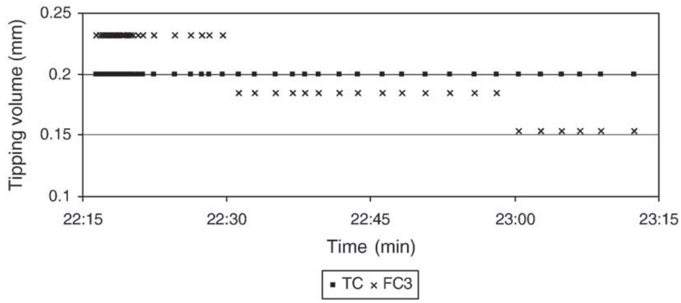

Fig. 6. A 1-hour period in the tipping-bucket rainfall time series as observed (TC) and after DC transformation according to the results for FC3, emission scenario A2 (FC3).

multiplied by the corresponding DCF obtained from the distributions shown in Fig. 4.

In the DC procedure, it is essentially assumed that the highest 15% of the RCA3 intensity distribution represents the full local intensity distribution. If so, the DCF distributions may be directly applied to the observed distribution. This, however, produced future changes in the seasonal mean intensities which were not entirely consistent with the relative changes estimated from RCA3 data (Table 2). The reason for this is likely that the estimated upper 15% is not sufficient for accurately representing the full local distribution, but a larger proportion would be required (this is also suggested from the underestimation of total long-term volume by the tipping-bucket gauge found in Hernebring (2006)). To account for this, the DCF distribution may be applied only to observed values above a certain threshold; below this threshold the lowest DCF_0 is used. The threshold value may be tuned to get changes in seasonal average intensities that are consistent with the RCA3 scenarios. The exact choice of threshold is not critical, but different values produce almost equally accurate results (generally a value of 0.6 mm/30 min was used). It should be emphasised that this procedure is used to get consistent changes of seasonal averages by small corrections of low intensities and it has in practice only a minute impact on the highest intensities as well as individual events.

Finally, the modified 30-min observations were converted back to tipping-bucket data. For each 30-min period, the

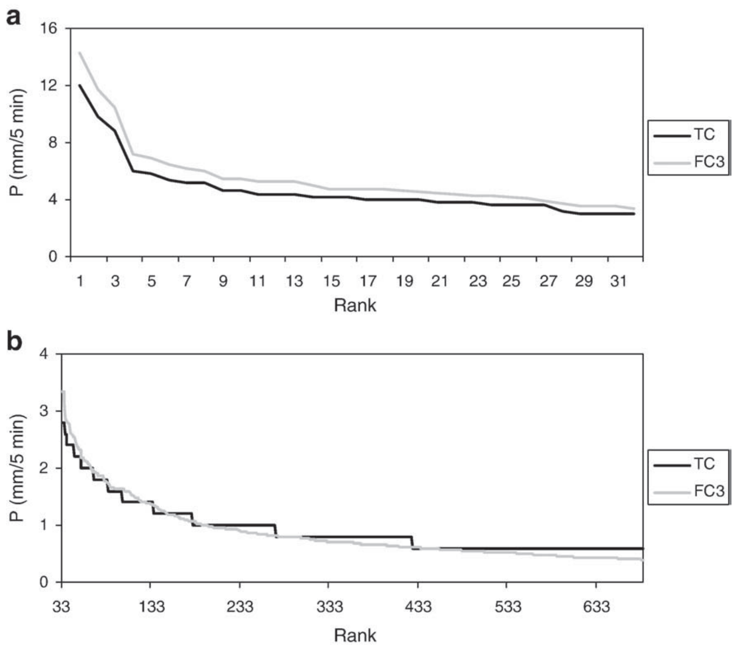

Fig. 7. Comparison between the highest 5-min intensities (a) and intermediate 5-min intensities (b) as observed (TC) and after DC transformation according to the results for FC3, emission scenario A2 (FC3).

Table 3
Properties of selected rainfall events as observed (OBS) and after DC-transformation according to the results for the different climate perspectives (FC1, FC2, FC3), emission scenario A2.

Date	Dur	Max				Vol			
		OBS	FC1	FC2	FC3	OBS	FC1	FC2	FC3
920821	23.3	0.6	0.57	0.59	0.46	25.2	21.9	21.6	16.8
940818	14.6	3.0	3.3	3.4	3.6	54.8	54.9	56.8	50.8
040825	11.4	3.8	4.2	4.3	4.5	33.8	33.6	34.6	31.5
970727	2.3	8.8	9.6	10.1	10.5	15.4	16.8	17.5	18.1
030729	7.0	12.0	13.1	13.7	14.3	93.0	99.4	104	104

Variables: duration (Dur; hours), maximum 5-min intensity (Max; mm/5 min) and total volume (Vol; mm).

modification was implemented by changing the volume of the tipping bucket in accordance with the DCF of the 30-min periods. For example, during a 30-min period with a DCF of 1.2, the bucket volume was changed to 0.2*1.2 = 0.24 mm. The final modified tipping-bucket series thus has the same "tipping times" as the original series, but a variable bucket volume that reflects the estimated changes of different rainfall intensity levels.

The result is illustrated in Fig. 6, for a 1-hour period in the evening of 980607, transformed on the basis of the results for FC3, emission scenario A2. In the beginning of the period the observed rainfall is rather intense, with 6 mm occurring in the period 22:00–22:30. This corresponds to a DC-factor of 1.16 and a conversion of the tipping-bucket volume to 0.2*1.16 = 0.232. In the period 22:30–23:00 the observed rainfall is less intense, 2.8 mm, which corresponds to a DC-factor of 0.92 and a bucket volume of 0.184 mm. In the period 23:00–23:30 the observed rainfall, DC-factor and bucket volume are further decreased.

4.2. Evaluation of modified series

To evaluate the effect of the DC method on a very high time resolution, the original and the DC-transformed tipping-bucket time series were converted into a 5-min resolution. Fig. 7a shows the change of the highest 5-min intensities (32 values, corresponding to intensities equal to or higher than 3 mm/5 min or equivalently 15 tippings/5 min) for FC3, emission scenario A2. The highest value, 12 mm/5 min for TC, is transformed to 14.3 mm/5 min, in line with $DCF_{99} = 1.19$ for FC3 (Section 3.2). For lower intensities, the difference decreases. Fig. 7b shows the change of intermediate 5-min intensities, between 2.8 mm/5 min (14 tippings) and 0.6 mm/5 min (3 tippings) for TC. In this figure, the discrete character of the tipping-bucket data is more clear than in Fig. 7a. The transformed data do not exhibit this discrete behaviour. In the application of DC-factors on a 30-min resolution, a certain observed intensity (expressed as a multiple of 0.2) was always modified by the same DC-factor. Thus at a 30-min resolution the discrete character remains. At a higher resolution it however disappears as a certain number of tippings will no longer correspond to a fixed intensity, but the intensity varies depending on the bucket volume during the period in question. In Fig. 7b it may be seen that the breakpoint between intensities that are increased and decreased, respectively, in this particular DC application is 1.2 mm/5 min for TC.

In Table 3, the resulting changes of some observed rainfall events are shown (scenario A2), to illustrate the function of the DCF distribution approach. The event on 920821 lasted for nearly 1 day with a low maximum intensity of only 0.6 mm/5 min and a total volume of 25.2 mm. In the modified data, the maximum value remains nearly constant for FC1 and FC2, and decreases to 0.46 mm/5 min for FC3. The total volume decreases substantially, by nearly 10 mm for FC3. The events on 940818 and 040825 were shorter but more intense with a maximum intensity of 3–4 mm/5 min. In these events the future maximum intensity increases systematically. The total volume, however, remains fairly constant for FC1 and FC2 but decreases for FC3. The event on 970727 was very short and very intense. As this event is strongly dominated by the maximum 5-min intensity (8.8 mm/5 min), the systematic increase of this value makes also the total volume increase similarly. Finally, Table 3 shows the properties of the most

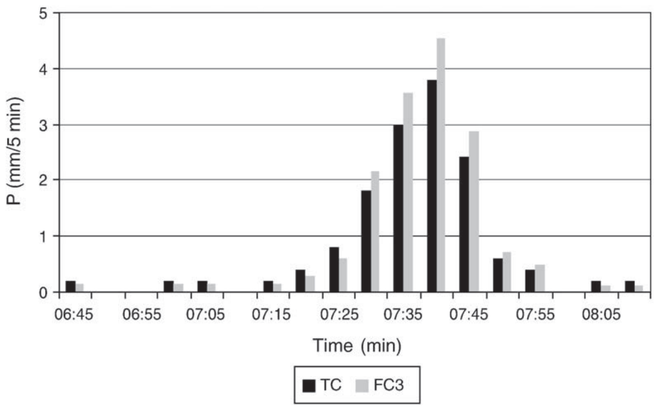

Fig. 8. The central part of event 040825 before (TC) and after DC transformation according to the results for FC3, emission scenario A2 (FC3).

intense rainfall event in the time series, totalling 93 mm in 7 h on 030729, of which nearly half of the volume occurred within 30 min. This 30-min intensity is nearly three times higher than the second highest in the data set. The maximum 5-min intensity is 12 mm/5 min, which gradually increases up to 14.3 mm/5 min for FC3 (corresponding to rank 1 in Fig. 7a). The total volume increases by more than 10 mm from TC to FC3.

In Fig. 8, the effect of the DC application is illustrated for the central part of event 040825 in Table 3 (in reality scattered rainfall occurred several hours both before and after the peak at 07:40). For FC3, the peak 5-min intensity increases from 3.8 to 4.5 mm/5 min whereas the surrounding low intensities decrease from 0.2 to 0.13 mm/5 min. Intermediate intensities either increase or decrease depending on the neighbouring intensities within the surrounding 30-min period.

A general expected effect of climate change on local rainfall in the mid-latitudes, based on both theoretical reasoning (e.g. Trenberth et al., 2003) and regional climate model output (e.g. Mailhot et al., 2007), is towards higher maximum intensities and shorter durations (and/or lower frequencies). For an event, this implies that an increase of peak intensity does not have to be accompanied by an increase also of the total volume. In ordinary DC, changes in peak intensity and total volume must be in the same direction, as the duration is fixed. By the intensity dependence, however, the DC method can allow for qualitatively different changes in peak intensity and total volume, as demonstrated in Table 3. Even if the duration is still fixed, a qualitative change in the expected direction is attainable by reductions of the low intensities in the beginning and end of the event and increases of central maximum intensities, as illustrated in Fig. 8.

4.3. Implications for urban drainage

In general terms, different impacts on the urban environment can be envisioned due to climate-induced changes in e.g. precipitation, all of which are not easily measured. In light of the changes indicated in previous sections, some of the possible impacts can be described as:

- Low-intensity rainfall events will cause no direct harm in the urban drainage system, although it is possible that this type of rainfall events may worsen the effect of following rainfalls if permeable areas may become saturated. There might, on the other hand, be impacts on the groundwater levels and the availability of drinking water sources, e.g. as a consequence of reduced seasonal rainfall volumes.
- Very high-intensity and extreme rainfall events are likely to cause increased basement floods, surface floods, combined sewer overflow and inflow to treatment facilities (wastewater treatment plants and storm water management structures, e.g. dams). Even though the total rainfall volume might decrease, the increased peak intensity will cause rapid runoff and sufficient infiltration capacity might not be available. If the rainfall is combined with thunderstorms leading to other problems such as electrical failure, the consequences will be even worse as the pumping facilities in the system and treatment plants may come to a stop, and thus cause more flooding.

When assessing impacts due to climate change, or extreme weather events, on existing urban drainage systems it is also important to learn where in the system the capacity is low, identify the most vulnerable locations. The DC modified rainfall generated in this analysis will be used as input to an urban drainage model set up for a catchment in the city of Kalmar, and results from this application will be presented in a follow-up paper. Preliminary results indicate that for emission scenario A2 the number of surface floods in the system will increase by 20% in FC1, 33% in FC2 and 45% in FC3, compared with the situation in today's climate (Olofsson, 2007; Berggren, 2007).

5. Summary and discussion

Five contributions and conclusions from this study are worth highlighting. (1) The RCA3 climate model 30-min precipitation from the grid box considered overestimates the rainfall volume as compared with local tipping-bucket observations, mainly owing to an overestimated frequency of low intensities. Maximum intensities appear reasonably well reproduced, if taking into account the difference in spatial resolution. (2) A percentile-based version of the Delta Change (DC) method makes it possible to describe changes of different rainfall intensity levels, and transfer these to observations. (3) In summer, the highest intensities are expected to increase by 20–30% until 2100, whereas low intensities as well as the total volume decrease. The pattern is similar in autumn with an even more pronounced increase of the highest intensities, 50–60%, whereas in winter and spring all intensity levels increase with approximately the same amount. (4) The DCF distributions may be transferred to an observed tipping-bucket rainfall time series by considering the bucket volume as a variable that is changed depending on the 30-min rainfall intensity. This facilitates the application in urban drainage modelling. (5) The DC methods makes it possible to represent qualitatively different changes in peak intensity and total volume of an event, which is required in light of expected future precipitation changes.

The proposed version of the DC method is thus envisioned to transfer future intensity changes to tipping-bucket observations in a more realistic way than simpler DC approaches. Even if the "tipping times" remain unchanged, the internal structure of rainfall events may be modified in different directions. Moreover, the highest and most important intensities are modified by a "tailor-made" DC factor. Further development of the DC method is conceivable, e.g. by focusing on properties of precipitation events and not only single intensities. Relative future changes in event volumes and durations can potentially be transferred to observations in a similar way to changes in the intensity distribution.

An important remaining issue concerns the mismatch in spatial scale between the high-resolution observations (point value) and the low-resolution climate model output (2500 km^2). As applications such as the present one are based on the assumption that future lower-resolution changes in rainfall are equal or at least similar to the future higher-resolution changes, especially 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. A key to bridging the scale gap may therefore be to analyse separately changes in the two different precipitation components described in the climate model: large-scale and convective. These components may be used to build downscaling models, relating grid-box averages to point observations, and such work is ongoing.

It must finally be emphasised that the results are based on two emission scenarios (A2 and B2) but simulated by one single global model (ECHAM4), from one single initial condition, and dynamically downscaled by one single regional model (RCA3). The results from other emission scenarios, models (and model combinations) and initial conditions are likely to differ. In particular, simulated extreme precipitation is known to depend on the process description in the regional model (e.g. Frei et al., 2006). A large ensemble of emission scenarios, models and initial conditions is required for uncertainty assessment, and work in this direction is ongoing to put the results presented here in a proper context.

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Paper II

Hydraulic impacts on urban drainage systems due to changes in rainfall, caused by climate change

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Hydraulic Impacts on Urban Drainage Systems due to Changes in Rainfall Caused by Climatic Change

Karolina Berggren[1]; Mats Olofsson[2]; Maria Viklander[3]; Gilbert Svensson[4]; and Anna-Maria Gustafsson[5]

Abstract: Changes in climate were a growing concern during the last decade and will be even greater in the coming years. When investigating the impact from changes in the climate on urban drainage systems, two challenges are (1) what type of input rainfall data to use and (2) what parameters to use to measure the impacts. The overall objective of this study is to investigate the hydraulic performance of urban drainage systems related to changes in rainfall, and through these hydraulic parameters describe the impact of climate change. Input rainfall data represent today's climate and three future time periods (2011–2040, 2041–2070, and 2071–2100). The hydraulic parameters used were water levels in nodes (e.g., as the number of floods, and frequency and duration of floods) and pipe flow ratio. For the study area, the number of flooded nodes and the geographical distribution of floods will increase in the future, as will both the flooding frequency and the duration of floods. **DOI: 10.1061/(ASCE)HE.1943-5584.0000406.**

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Introduction

The design and operation of an urban drainage system is closely associated with the rainfall characteristics of the local urban area, especially the intensity and amount of rainfall. The increasing global mean temperature has been a concern for several years, as the hydrological cycle intensifies accordingly, and a larger number of heavy precipitation events will occur in the 21st century is very likely, according to the Intergovernmental Panel on Climate Change (IPCC 2007). When assessing the impact of climate change, especially precipitation changes, on a city through the urban drainage system, some problems need to be taken into account. Two of the main problems are (1) the type of input rainfall data used for model simulations to represent changes in the future and (2) how the urban drainage impacts should be measured to reflect and accurately describe the event and system characteristics. Regarding the input data and especially for precipitation, a decision needs to be made on the global circulation models (GCM) and the scenarios to use. Information from GCMs has a resolution in both time and space that often is too low to be used directly for urban hydrology simulations. Even though regional downscaling from these models gives better results, possibly well enough for larger catchments (Guo and Senior 2006), they often do not provide results directly applicable for urban hydrology [ideally, 1 min temporal resolution and 1 km^2 spatial resolution, according to Schilling (1991)]. A further downscaling in time and space is often needed. Previous approaches to this problem for urban hydrology have been scaling factors. For example, Niemczynowicz (1989) used design rainfall, which was changed with fixed percentages (+10, 20, and 30%, for a Swedish case study). Waters et al. (2003) used a similar approach for a Canadian case study. Semadeni-Davies (2004) varied precipitation amounts between −10 and +40%, combined with temperature that varied between −5 and +15%, for a Swedish case study, which also included snow melting. In contrast, Guo (2006) and Denault et al. (2006) used intensity-duration-frequency (IDF) relationships of historical rainfall series to detect trends for future rainfalls. A more direct approach regarding the use of climate model information and factors of change is the so-called delta change method. Semadeni-Davies et al. (2008) used the delta change approach for urban hydrology, in which present and future climate simulations from a regional climate model were compared to determine monthly changes that were then applied to observed rainfall data (in two groups, drizzle and storm). Olsson et al. (2009) further developed this approach with more focus on rainfall intensity and used a regional climate model to make comparisons between a control period (present time) and future periods. These generated diversified factors applied rainfall of different intensities and according to the seasons of the year (summer, autumn, winter, and spring). Larsen et al. (2009) presented another approach, also related to climate model data comparisons (control period and future period) from a regional climate model but focused on changes in the return period for different rainfall durations. The study resulted in suggestions about changing factors for several European countries, which may be applied to design rainfall. The chosen approach for this study is the delta change method, with a focus on intensity and seasons of the year as described by Olsson et al. (2009), which also enables the use of time series and the possibility of examining impacts over time. When describing and measuring impacts on

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urban drainage systems, water professionals refer to performance indicators related directly to the performance and capacity for different aspects such as technical (e.g., hydraulic), environmental, and economic (e.g., Bertrand-Krajewski et al. 2002), and even more if also considering sustainability (e.g., Ashley et al. 2008; Ellis et al. 2004). Parameters describing impacts on urban drainage systems from climate change and changes in rainfall have focused on the number of floods and affected properties (e.g., Ashley et al. 2005), the number of surcharged pipes (e.g., Waters et al. 2003), and changes in runoff volume (e.g., Semadeni-Davies et al. 2008; Bruen and Yang 2006), discharge (e.g., Dougherty et al. 2007), and overflow volumes (e.g., Niemczynowicz 1989). This paper emphasizes the hydraulic performance in the urban drainage system. The overall objective is to investigate hydraulic impacts on urban drainage systems as a result of changes in rainfall (intensity) from climate change. Further, this paper demonstrates how hydraulic parameters can be used to give a more diversified view of urban drainage systems' vulnerability and capacity. The paper takes a case study approach using urban drainage model simulations. The rainfall used represents different climate periods—today, the near future (2011–2040), the intermediate future (2041–2070), and the distant future (2071–2100).

Method

Study Area

The study area is a small suburb on the southeast coast of Sweden (close to the city of Kalmar), which has a population of about 3,000 and a contributing catchment area of 54 ha, of which about 37% is impervious. The urban drainage system is separated, and the stormwater model used for simulations of the area was built by DHI (2008). The model consists of about 465 gully pots (subsequently referred to as nodes). Measurements (rainfall and pipe flow) and associated calibration of the model were performed according to standard procedures with iteration techniques (Håkan Strandner, DHI Water and Environment, personal communication, October 2010). The validation of the model is shown for five nodes, of which one is close to the outlet, and a total of 33 peak flows from six rainfall events (Fig. 1). The model underestimates the peak flows by on average 13% but shows good agreement overall. The measured rainfall series of about 2 months length had a maximum intensity of 145 mm/h. The system has three outlets (two in the north and one in the south of the system) and the time of concentration for the area is about 50 min. The main pipe section is about 3,300 m long, with diameters ranging from 500 mm to 1,000 mm, the pipe material is concrete, and the mean slope is about 0.8%. The distance to the sea is about 3 km and the height at the outlet is about 5 m above sea level. For most of this paper, all 465 nodes were used for the analysis; but for the frequency and duration analysis, the data volume had to be reduced because of the large amount of data produced. A total of 120 nodes were selected as representative of the system for the result output file. The selection of nodes was performed as a standard procedure on the basis of the following criteria: (1) nodes representing swales were removed from the result file, (2) nodes with depths of less than 1.0 m were removed from the result file (to be able to consider a level below the ground in the system, subsequently called critical level, as a complement to the ground level), and (3) if several nodes were very close to each other, only a few of them were kept for the result file. The Mike Urban model performs the simulation in two parts; first, the runoff simulation is performed (in this case, the time area method is used with time step 60 s), then the network simulation uses the runoff results as input. Network simulation was performed with a long time simulation (LTS) approach, which is a standard procedure. For the LTS approach, the specific time when rainfall occurs (including the associated runtime in the system) was selected and the other time (e.g., long periods during the winter) was not included. Thus, the total simulation time will be substantially shortened. The network simulation uses the dynamic wave model type (recommended) and time steps (min: 10 s, max: 60 s), with the saving interval of 1 min.

Rainfall and Climate Model Input Data

For the study area, rainfall was measured as tipping bucket rainfall data with 0.2 mm volumes and point source rainfall. From the total series of available data (1991–2004), a 10-year-long period (1993–2002) was selected (Fig. 2). The number of years was chosen to be equal to the climate model series (a total of 30 years, but the results mean for each 10 years). According to design standards for stormwater systems in Sweden, the system should cope with rainfalls for a 10-year return period. Therefore, the 10 years were also chosen to include rainfalls of such magnitude. The most intense rainfall events occurred in 1997–2007 and 1994–2009. From the statistical analysis (Hernebring 2006; DHI 2005), the event in 1997 had high intensity during shorter times (duration: 2.3 h, volume: 15.4 mm, max intensity: 238 mm/h), whereas the event in 1994 had a longer duration (duration: 8.1 h, volume: 27.6 mm, max intensity:

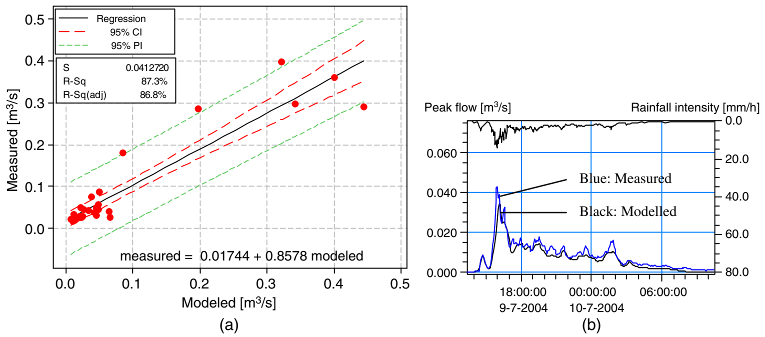

Fig. 1. (a) Measured and modeled peak flow values (m^3/s) for five nodes (33 values). Software: Minitab16 (Minitab 2010); (b) example hydrograph for a node in the system (DNB0202) and corresponding rainfall hyetograph from the validation model runs

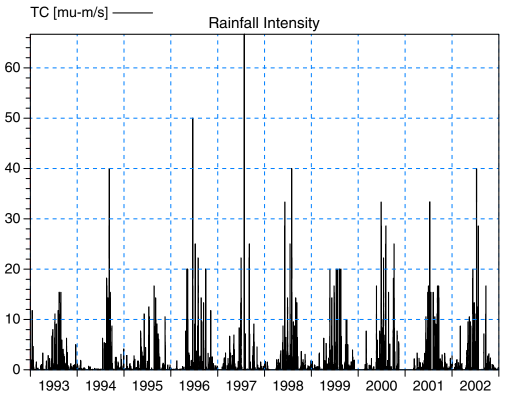

Fig. 2. The observed rainfall series, tipping bucket volumes converted to intensity [μm/s], for 1993–2002 (TC). Data from Hernebring (2006), software: Mike Urban (DHI 2008)

144 mm/h). The observed rainfall series (1993–2002) is used as a baseline scenario assumed to represent the climate and rainfall of today (later on called TC, today's climate). For the future rainfall events, the delta change method (Olsson et al. 2009) was used, in which differences in climate model data were applied to observed rainfall. The climate model input data were from the regional climate model RCA3 by Rossby Center (Kjellström et al. 2005), which covered the European continent and had a resolution of 30 min and grid sizes of 50 km by 50 km. The RCA3 originated from the global circulation model ECHAM4; and for this paper, the future global emission scenario SRES A2 (defined by Nakicenovic et al. 2000) was used. A2 is a high-medium emission scenario, described as, for example, a heterogeneous world with a continuously increasing global population and regionally oriented economic growth (Nakicenovic et al. 2000). The A2 scenario is one of the most commonly used scenarios for impact assessments, for example, by Semadeni-Davies et al. (2008) and Larsen et al. (2009). Only one scenario was used, as the focus for this paper is the hydraulic performance and responses in the urban drainage system rather than differences between scenarios.

Delta Change Method

The delta change method involves several steps (more details in Olsson et al. 2009), with the most important being these three. (1) Comparison of RCA3 data from a control period (1971–2000) with the following three future time periods: near-future climate (2011–2040), intermediate-future climate (2041–2070), and distant-future climate (2071–2100). The comparison was performed related to the rainfall intensity and divided according to the seasons of the year (summer, autumn, winter, and spring). The rainfall events were sorted according to intensity, and thus the difference between periods (future minus control period) gave the factors of change (delta change factor: DC factor). From the 30-year main periods, values of the DC factors for each of the three included 10-year periods were formed, and the DC factor distribution was averaged over integer percentiles and then averaged for the 30 years to smooth out variations. The DC factors for the highest intensities (the 99th percentile) ranged from about 10–19% for the summer period, 28–63% for autumn, 20–61% for winter, and 8–24% for spring. (2) Aggregation of the observed tipping-bucket rainfall volumes in 30-min intervals (to be compatible with CMD data), divided in seasons of the year and sorted according to intensity. (3) Application of DC factors to the observed series aggregated in 30-min intervals, which were later again formed as tipping-bucket volumes, providing a new tipping-bucket rainfall series with diversified volumes (according to changes from the applied DC factors). The new rainfall series had a length of 10 years and represented future climate periods of near-future climate (2011–2040, called future climate period 1, FC1), intermediate-future climate (2041–2070, FC2), and distant-future climate (2071–2100, FC3).

Parameters

The parameters chosen to measure hydraulic impacts on the urban drainage system were water levels in nodes and pipe flow ratio in links. The water levels in nodes were measured as maximum from both a ground level (GL) and a so-called critical level (CL) perspective, where GL and CL can or cannot be exceeded. The CL was set at 0.5 m below the GL. The maximum water level was used primarily to describe differences between the simulated periods and was statistically compared within matched pairs of nodes. The analysis was performed as a t-test at a 95% confidence level. The software used was Minitab 16 (Minitab 2010). The parameter water level in nodes was measured not only to reflect the response from the maximum event (one event) in the system but also the whole time series (several events) for frequency and duration. The frequency describes how many times the levels (GL and CL) in the nodes were exceeded. Duration describes how long water was over the GL (and CL), and was measured as the total duration for the period, the duration within unique flood events, and as a maximum duration for the most affected node within the simulated period. Pipe flow ratio (Q/Qf) is the ratio of the actual flow rate (Q) and the flow rate when the pipes were running full (not pressurized) in the system (Qf). The Mike Urban software measures Q/Qf once or twice per link, depending on the lengths of the pipes; thus, the total number of points was 523.

Results

The maximum occasion for the hydraulic parameters in the system was closely related to the maximum rainfall events; for TC, most of the maximum water levels in the nodes was caused by the rainfall in 1997–2007, and for the delta-changed rainfall FC3 the maximum event was mainly related to rainfall in 1997–2007 and 1994–2009. For the frequency and duration of floods, other rainfall events also contributed to the results.

Water Levels in Nodes

The maximum water levels in nodes gave more information about the difference between periods and were higher for all future scenarios (FC1, FC2, and FC3) than for today's (TC) levels (at a confidence level of 95% and confirmed by the statistical

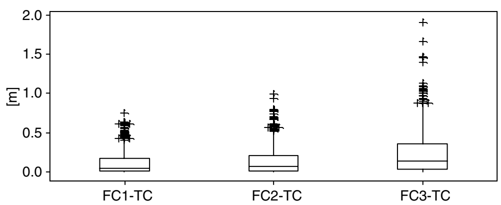

Fig. 3. Maximum water levels in nodes, differences between baseline scenario TC and FC1, FC2, FC3. Software: Minitab16 (Minitab 2010)

Table 1. Differences between Baseline Scenario TC and Future Period FC3 for Maximum Water Levels in Nodes and Pipe Flow Ratio

		Area A	Area B	Area C
Link diameter	(mm)	300–400	400	225
Node depth				
	min-max (m)	1.55–1.78	1.72–2.22	2.07–2.17
Max water level (FC3–TC)				
	min-max (m)	0.87–1.09	0.18–0.31	0.38–0.61
	mean difference (m)	1.01	0.25	0.51
	mean difference (%)	62	13	24
Pipe flow ratio				
	min-max (–) (FC3)	0.40–2.28	1.27–1.31	0.82–2.29
	mean difference (–) (FC3-TC)	0.18	0.05	0.37
	mean difference (%) (FC3-TC)	38	4	17

Note: Each area A, B, and C consists of three selected nodes and the location of the areas (A, B, C) shown in Fig. 6.

t-test). The maximum difference in the nodes was 1.9 m (an increase of 385%) for FC3 compared with baseline scenario TC. For 18% (82 nodes) of all nodes, the difference was more than 0.5 m, and for 3% (14 nodes) it was more than 1 m (FC3-TC) and flooding occurred in five of these nodes. The difference in maximum water levels in nodes was presented for FC1, FC2, and FC3 related to baseline scenario TC (Fig. 3), and values for three selected areas in Table 1. The number of nodes flooded (water exceeded GL) in today's situation increased for future periods (FC1, FC2, FC3). The number of nodes for which water exceeded the critical level in the system (CL) was naturally higher at all periods and increased from today to future periods. Table 2 shows the number of nodes affected. The total frequency (all nodes) and the maximum frequency (one node) were increasing from TC and in the future (Table 3) as well as the number of floods in each node shown as intervals in Fig. 4. The total frequency was more than doubled for exceeding GLs for TC compared with FC3 (25 vs. 75), and about doubled for CL. Nodes flooded one to two times in TC compared with FC3 were doubled for GL (from 5 to 11) and almost doubled for CL. The overall tendency was that future precipitation increases both the number of nodes flooded and the flooding frequency. Because of the large amount of data produced during this operation (and for analysis of the duration), only the selected nodes (120) were included in the analysis. Fig. 5 shows the increase in flood duration from today and during the future periods described from unique flood events (the same node may be flooded several times). The left diagram shows the duration of real flood events (based on the GL), whereas the right diagram presents

Table 2. Number of Nodes Flooded (GL) and Critical Level Exceeding (CL −0.5 m) for TC, FC1, FC2, FC3

	TC	FC1	FC2	FC3
GL	15	24	26	38
CL	52	83	90	117

Table 3. Frequency and Duration, Total Value (All Nodes Included) and Maximum Value (One Node) for TC, FC1, FC2, FC3

		Frequency				Duration			
		TC	FC1	FC2	FC3	TC	FC1	FC2	FC3
GL	Total	25	42	54	75	9:08:49	15:58:25	21:00:05	31:05:46
	Max	12	16	24	26	0:44:04	1:02:10	1:11:33	1:48:16
CL	Total	119	154	189	222	50:08:54	71:32:26	91:42:42	116:04:07
	Max	31	34	38	47	1:17:31	1:56:43	2:07:13	2:32:06

Note: Frequency [-], Duration: [H:Min:S].

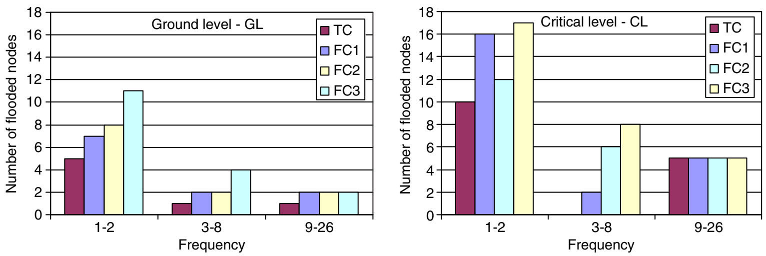

Fig. 4. Frequency of "flooded" nodes, to the left: ground level exceeding, to the right: critical level (−0.5 m) exceeding. For TC, FC1, FC2, FC3

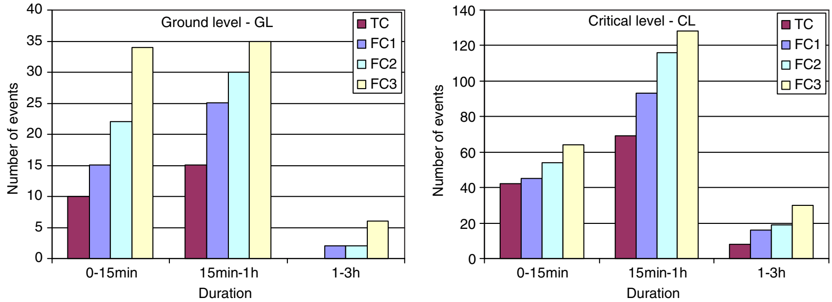

Fig. 5. Number of flooding events for different durations, to the left: ground level exceeding, to the right: critical level exceeding (−0.5 m); for TC, FC1, FC2, FC3

an indication of the system's capacity (based on the CL). Even though the number of events differs greatly between the diagrams, the tendency of increased duration is similar. Note that the scale in the diagrams differs. Table 3 presents the total duration and the maximum event (for the maximum node). The maximum duration is doubled (CL) or more (GL) when comparing TC and FC3; for GL, the increase is about 1 h, which may have an impact on the damage in the city caused by flooding.

Pipe Flow Ratio

Pipe flow ratios for the maximum flow provide more information about system capacity shortage and are presented graphically for TC and FC3 in Fig. 6, as are the nodes for which water exceeded GL and CL. For TC, floods occurred primarily in two places, whereas in future period FC3, floods will have spread over a wider area and to other locations as well. The three circles show areas (A, B, C) in which new problems will occur in the future. In Table 1, values are shown for FC3 relative baseline scenario TC. The maximum pipe flow ratio (Q/Qf) in the network increased between the two periods. For the link with the highest value, Q/Qf is 4.9 for TC and 5.1 for FC3, but the main part of the measuring points had values lower than 1, which means that the pipes were not running full. For TC 406, 78% of the total 523 measuring points in the links (one or two per link) had values of Q/Qf below 1, and for FC3 it is 368 (70%). The analysis of the number of affected nodes in Fig. 6 was based on all 465 nodes in the system, but some of the nodes could have been flooded several times, as this parameter is related to the maximum event.

Discussion

A study regarding the future often involves climate models, as they take into account several future aspects, for example, emission scenarios related to different developments of the world. They provide information about future possible developments but are also associated with uncertainties. But although the uncertainty of the analysis increases and cannot easily be estimated when including climate models, they still provide good information about the complex situation. Several global circulation models and regional models are available, but they have different focus and resolutions. For this case study, the most convenient model choice is the regional model with the most focus on the study area (RCA3 describes Europe, has a basis in Sweden, and focuses on the Baltic Sea, which is important for the relatively coastal Kalmar). Furthermore, the use of observed local rainfall as the basis for the delta change approach also gives more focus on the specific study area. Thus, local characteristics are taken into account. It is also common for future studies to use several emission scenarios. For this case study, only the A2 scenario was used because the focus was on the hydraulic performance and responses in the urban drainage system rather than differences between scenarios. However, the highest factors produced by the delta change method for A2 could be compared with those associated with B2, which is another commonly used scenario (described as low-medium by Nakicenovic et al. 2000). In Olsson et al. (2009), both A2 and B2 scenarios were studied for the Kalmar area using the same RCM and method. Although the general description of the scenarios is different (high-medium versus low-medium) for the Kalmar area, the delta change factors for A2 and B2 are similar (only slightly different distributions over seasons) (Olsson et al. 2009). The highest factors can also be compared with other studies, although not directly, as they often are not produced from the same climate model, method, or time perspective. Larsen et al. (2009) suggested average factors for rainfall of 100-year return periods in the range of 15–35% for the major part of the European countries, which are similar to the factors used in this paper. The study was based on another RCM (HIRHAM4), and there were some problems related to the Baltic Sea, resulting in factors specific for Sweden being much higher than for other countries. A general problem regarding urban drainage models is that the calibration and verification of the models are often based on rainfall events of moderate day-to-day character and not extreme events. For the more extreme events associated with future climate change (and events occurring today with a long return period, e.g., 100 years), there are uncertainties about how the model can be extrapolated to incorporate such events. For this study, the measured rainfall series used for calibration/verification of the urban drainage model has a maximum intensity of about 145 mm/h, which is lower but in the same range as the maximum events (144–238 mm/h) in the baseline scenario for today's climate (TC). The model underestimated the peak flows because the contribution from the previous areas were not being modeled correctly in total. The purpose of this study was to consider the differences between model simulations (periods) and to look more closely at what the output parameters showed and how the information could be used when assessing hydraulic impacts on the system. The results were also not intended to be used directly for the municipality urban drainage adaptation plans and therefore are deemed adequate for comparative purposes. When measuring the impacts, water levels in nodes provide information about the number of flooded nodes, a commonly used parameter that describe the impacts on the urban drainage system. This information indicates the impacts on the urban area, and even more information is provided

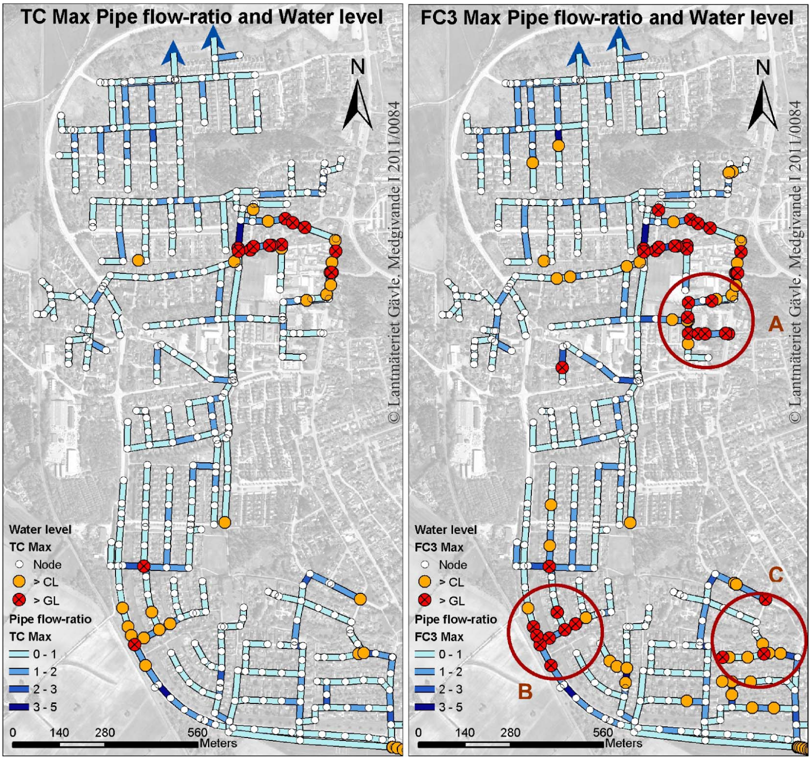

Fig. 6. Maximum pipe flow ratio (darker for higher values), flooded nodes for which the ground level (GL) was exceeded (dark dots) and nodes for which the critical level (CL) was exceeded (light dots), for the baseline scenario (TC) to the left and for the future time FC3 to the right. The circles represent new areas (A, B, C) in which flooding will occur in the future (background image ©Lantmäteriet Gävle 2011. Medgirande I 2011/0084)

if this parameter is considered not only from the ground level (floods) perspective but also from a critical level below ground (in this paper, 0.5 m below ground). The number of nodes affected by exceeded critical levels gives additional information about system capacity, as areas close to being flooded can be located, i.e., a type of safety margin. However, the number of nodes affected only gives information about the maximum event and not the response over time, which is also the case for maximum water levels in nodes and the pipe flow ratio. These parameters are still beneficial. The maximum water levels in nodes can provide more specific information about the difference between simulations (e.g., TC vs. FC3) but should be used in relation to the number of nodes affected by flooding and exceeded critical levels. The pipe flow ratio provides information about the capacity of the system, especially if presented graphically, low-capacity areas can be located. The increase in the pipe flow ratio can 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 damage can have economic consequences for both property and network owners. To take into account the time series perspective, the frequency of floods (from both the ground-level perspective and the critical level) provides information about system capacity and its behavior over time. Several nodes were flooded several times, and the rainfall events that caused this were not the same and combinations of events also contributed to the total number. The increase in duration indicates the level of damage caused by flooding if related to the specific urban area properties and public services affected. This is important for the continuation of the impact studies. The hydraulic impacts on the urban drainage system should be presented in relation to the urban area's specific attributes to provide more information to the stakeholders and decision makers. The hydraulic parameters in this paper were chosen to describe the impacts on urban drainage systems attributable to changes in rainfall (especially intensity) caused by climate change. The advantages of these parameters are their almost immediate hydraulic response and their simple presentation of system capacity.

Conclusions

The hydraulic parameters used in this paper provide a broad view of the hydraulic performance in the system and measure hydraulic impacts in a more diversified way than just the number of flooding events on the maximum occasion. The maximum water levels in nodes can highlight differences between time periods; however, they should be used in relation to the number of flooded nodes. A critical level in the system nodes below the ground level improves an understanding of system capacity. The frequency and duration contribute to an understanding of system capacity over a period, as the maximum rainfall event causing the highest number of floods can result from both a single event and combinations of rainfall events. The pipe flow ratio also improves an understanding of system capacity, and critical areas can be located when presented graphically.

This paper also demonstrates that more urban flooding events are to be expected in the future for the study area. The number of floods, as well as the frequency and duration of floods, will increase in the future periods (FC1: 2011–2040, FC2: 2041–2070, FC3: 2071–2100). There are differences between the time periods and, as expected, the conditions regarding floods will also be worse in the distant future compared with the near future.

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Paper III

Climate Changed Rainfalls for Urban Drainage Capacity Assessment

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RESEARCH ARTICLE

Climate changed rainfalls for urban drainage capacity assessment

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Guidance on what type of rainfall to use when assessing hydraulic capacity of urban drainage systems under climate change is unclear; focus is mainly on what climate factors to use. Based on a case study in Kalmar, Sweden, this paper compares system performance using two design rainfalls, Block rainfalls and Chicago Design Storm (CDS), and selected observed rainfalls, with two methods of addressing future climate: a constant factor and Delta Change (DC) factors that depend on rainfall intensity. The use of CDS rainfalls presents the maximum hydraulic response, whereas Block rainfalls give lower responses but identify critical durations in the system, which may be useful addressing adaptation actions. Observed rainfalls of target return periods gave similar responses to CDS rainfalls, and can be applied with DC factors to address future changes in both intensity and volume. Differences between the two methods indicate a high dependence related to the maximum factors applied on the rainfalls.

Keywords: climate change; delta change; design rainfall; observed rainfall; rainfall-runoff analysis; stormwater modelling

1. Introduction

The evaluation and assessment of hydraulic capacity of urban drainage systems has become increasingly important to account for new urban development and likely increases in intense rainfall due to climate change (IPCC 2007 [Intergovernmental Panel on Climate Change]). However, the proper way to assess system capacity is a complex question even without addressing climate change. Urban drainage systems evolve to reflect the historical and developing character of the area and rainfall climate, and changes may affect the ability of a system to meet its required level of service.

When evaluating the performance of an urban drainage system, the European standard EN 752 (EN 2008) and associated national recommendations (for example in Sweden, SWWA 2004 [Swedish Water and Wastewater Association]) give an important framework. However, these recommendations do not always give clear guidance on how to address existing systems, for example: (1) what rainfall data to choose (e.g. time series, single event, design rainfall, synthetic rainfall, observed rainfall); (2) how to account for climate change (e.g. climate model data, global or regional models, scenarios, method of downscaling or other uplift factor technique); (3) the level of detail needed to adequately model the system; and (4) how to consider multiple parameters of change and take these into account (e.g. other climate parameters besides rainfall changes, population and urban area changes, and changes within the urban drainage system). Different national interpretations of the standard can also bring uncertainties. In this paper, focus is on the rainfall and climate change, as rainfall is the prime driver for urban runoff and drainage needs, and the future changes in the climate will affect rainfall behaviour.

There are several ways to take climate change into account, but it is not clear which one is most feasible and uncertainty levels are difficult to assess. Besides rainfall, other important aspects when assessing capacity of an urban drainage system are: (1) the character of the catchment – size, slope, shape, imperviousness, pervious area contribution, etc., which affect times of concentration for both subareas and the whole urban catchment and thus govern the most appropriate rainfall durations to be used; (2) rainfall resolution in time and space - short time steps and point rainfall is recommended for most urban catchments (e.g. Schilling 1991) and availability of good quality data records; (3) regulations regarding level of service for the specific catchment – which will define the return period of the rainfall, or whether return period of actual flooding is required; (4) Model type used, the most recent recommendations are to use combined hydraulic-hydrological components models (1D/1D or 1D/2D, e.g. Leandro *et al.* 2009).

Depending on the purpose of the study, time series and single events can be used as input rainfall. Time series run

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in a continuous simulation may give a better understanding of rainfall variability and the impact of antecedent hydrological conditions, provided that the model includes the hydrological processes to simulate the effects of soil water content on pervious area runoff. However, when modelling effort, computer capacity and run time are limiting factors, single event design rainfalls, obtained from intensity-duration-frequency curves (IDF) are usually adopted. In Sweden, a Block design storm (also called a Uniform distribution storm (Marsalek and Watt 1984)) is recommended for assessing the hydraulic capacity of existing systems, and a varying intensity design storm profile (e.g. Arnell 1982) is recommended for designing new systems (e.g. CDS, the Chicago Design Storm (Keifer and Chu 1959)). Similarly designed storms, based on standard IDF curves, are commonly used in most parts of the world.

Local rainfall records measured with high resolution are preferable, both to provide measures to update local rainfall statistics, but also for the use in urban drainage modelling as a complement to design rainfall. Lack of local data is sometimes a problem in Sweden as the local measurement network is often quite sparse. IDF statistics for Sweden are available (Dahlström 2010, recommended in SWWA 2011), although the most recent evaluation of rainfall records has not shown statistically significant regional differences as in the earlier evaluation (Dahlström 1979, recommended in SWWA 2004). These differences may influence the evaluation of existing system performance and the design of new systems. For example in the Kalmar area (south east of Sweden) design intensity of a 10 year return period rainfall is 12-20% higher in the new recommendations compared with the earlier.

Rainfall statistics are also not static over time, due to the effects of natural variability and climate change. Rauch and De Toffol (2006) for example, found no consistent trend of increased extreme rainfall events, analysing six data series of 19–55 years in length from four countries, whereas results from Denmark showed a general increase of rainfall intensities in the country, with regional variability and a tendency of larger extreme events in the eastern part (Madsen *et al.* 2009). Although, as historical rainfall records often are too short to detect trends of change, and as uncertainty increases when extrapolating any trends far into the future, climate models are being used instead to generate future scenarios. Yet rainfall data output directly from a climate model is often too coarse in resolution (temporal and spatial) for use in urban drainage modelling, as short time steps (about 1 min) and point rainfall is recommended for most urban catchments (e.g. Schilling 1991). Therefore methods of translating trends from climate models onto observed data are needed.

National guidelines for the use of climate factors are available in many countries, e.g. in Sweden with regionally defined climate factors (SWWA 2011), and in Denmark with factors assigned to different return period of rainfalls (Arnbjerg-Nielsen 2012). Applying climate factors added as a constant uplift to single rainfall events is the most common approach in urban drainage practice (e.g. Niemczynowicz 1989, Waters *et al.* 2003, Semadeni-Davies 2004, Ashley *et al.* 2005, Denault *et al.* 2006, Nielsen *et al.* 2011). The factors differ from each study, due to e.g. the specific region studied, the climate projection used, and the method used to identify factors of change. Another approach, where time series rainfall is available is to use a more detailed Delta Change method focusing on differences in volume (e.g. Semadeni-Davies *et al.* 2008a, 2008b), in intensity (Olsson *et al.* 2009, 2012, Nilsen *et al.* 2011), over periods of months (Semadeni-Davies *et al.* 2008a, 2008b) or over seasons (Olsson *et al.* 2009, 2012), and possibly considering dry periods between rainfall events (Olsson *et al.* 2012). Other less used methods are based on the identification of trends in observed historical data (e.g. Denault *et al.* 2006), and climate analogue techniques (e.g. Arnbjerg-Nielsen 2012).

The uncertainties involved with the use of climate models and emission scenarios are, however, very difficult to assess, and one recommendation is to use a range of climate models and scenarios (Willems *et al.* 2012a, 2012b), as for example in IPCC Special report (IPCC 2012) which suggests that today's rainfall of 20 year return period for Northern Europe would be closer to a return period of 10 years (on average) in the future (2081–2100). Defining changes with a return period concept or climate uplift factors are similar, a corresponding factor for increasing a 10 year rainfall to a 20 year rainfall (as suggested by IPCC 2012) is 1.25-1.26 using the Swedish general rainfall statistics by Dahlström (2010). A recent report by Swedish Meteorological and Hydrological Institute (SMHI) also provides general future climate factors for Sweden based on an ensemble of six climate projections for 10 year return period rainfall, yielding climate uplift factors of 1.13–1.35 (average of 1.23) for rainfall of 30 min duration and time period 2081–2100 (Olsson and Foster 2013). All these factors suggest that the average increase of future rainfall for Northern Europe and Sweden are close to 1.25 (for the future time period 2071–2100), which corresponds with recommended urban drainage factors (SWWA 2011) for the same time period of 1.05–1.30 (level depending on the location in Sweden). The use of simple factors is attractive for urban drainage applications where practical issues are involved, such as time and resources available for model simulations. However, even a limited number of time series simulations should provide useful information about future system capacity.

With all these issues in mind, considering the nature of the urban drainage system and the complexity in assessing its capacity: what rainfall should best be used when also taking into account climate change?

The objective of this paper is to investigate several 'simple' approaches, examining the differences in urban drainage model response from using design rainfall (Block rainfall and Chicago design storm - CDS) or observed rainfall (single events), considering both current and future climate conditions, with two adjustment methods: constant uplift (1.2) and a variable Delta Change (DC) method. The investigation is based on a case study of a suburb of Kalmar on the southeast coast of Sweden, where flooding from a severe storm in 2003 initiated detailed assessments of the drainage system using Mouse and MikeShe models (DHI 2008).

The original contribution from this paper is in examining established ideas (e.g. CDS tends to estimate higher impacts compared with a Block rainfall approach) in relation to emerging ideas about climate change (adding a climate factor, with two alternative methods). The study adds knowledge related to the assessment of hydraulic performance of urban drainage systems due to climate change: what rainfall data to use; and what method to use when accounting for climate change (on rainfall characteristics). The paper shows, from a practitioner perspective, the differences and limitations involved in variously defining rainfall inputs and thus informs the development of future recommendations as to what rainfall inputs to use for drainage capacity modelling. Additionally, a short comparison of evaluation parameters assessing urban drainage hydraulic impacts is provided in this paper.

Other parameters of change (e.g. other climate parameters than rainfall, or urbanization of the catchment) are not studied in detail. Urbanization of an area (increased imperviousness) will, however, increase the magnitude of impacts on runoff and hydraulic performance (e.g. Semadeni-Davies *et al.* 2008a, 2008b, Tait *et al.* 2008), both locally and for the whole catchment (depending on how the increase in imperviousness is distributed in the catchment). Runoff pattern and time of concentration may also change. Such changes will not influence the choice of rainfall type (design storm) and method accounting for climate change, but may enlarge the impacts seen in the catchment. Current drainage practice is moving towards more green/permeable solutions, such as infiltration facilities integrated into urban areas, which also may alter runoff patterns and times of concentration typically reducing runoff volumes and peaks and prolonging times of concentration (Ashley *et al.* 2007).

Climate impact due to changes in the sea level (or water level in lakes and rivers) is not relevant in the study area, as the catchment is at least 3 m higher at its lowest point than the suggested change in sea level (and not close to lakes and rivers). Such changes would not affect the choice of rainfall, but could cause problems at the urban drainage outlets (e.g. water infiltrating into the system due to higher groundwater level).

Future changes in the summer potential evapotranspiration are about 0–10% (Kjellström *et al.* 2009). The effect of such a change during an event will be small (due to the low evapotranspiration rate and short storm duration), but long-term influences on the soil water content (initial conditions) could be important. A pilot study (unpublished data) for the Kalmar area has however suggested that soil moisture content will be little affected by future conditions (based on average evapotranspiration and precipitation changes as given by Kjellström *et al.* (2009)). In the current study initial soil moisture has been set to the recommended MikeShe value of field capacity, and this relatively wet condition may have led to higher runoff volume and peak flow from permeable areas than if the soil water content had been set lower. Any effects on the conclusions of this study, where the focus has been on relative differences in results from using various types of storm rainfall input, are considered to be small. Yet, future long term impacts due to increased evapotranspiration, and the influence on soil water content as well as groundwater levels, are important issues that are being addressed in further research.

2. Method

2.1 Study area and model

The study area in Kalmar (SE of Sweden) has a population of about 3000, a total contributing catchment area (Figure 1) of 2.27 km^2 (12% impervious), and area directly connected to the urban drainage system of 0.54 km^2 (37% impervious). The urban drainage system is separate, and the storm water model used is a coupled 1D hydraulic and 2D surface runoff model (Mouse and MikeShe, by DHI (2008)). Such a coupled model is necessary to study flood dynamics on the urban surfaces (e.g. Leandro *et al.* 2009), and Mouse and MikeShe or MikeUrban and Mike21 (MikeFlood) are commonly used approaches in Sweden. The Mouse model handles the impervious area runoff and pipe hydraulics, using 440 nodes (mostly gully pots and manholes) feeding three outlets (two in the north and one in the south of the system). The main outlet is in the north (about 70% of all the runoff). The main pipe section is about 3300 m long, with diameters ranging from 500 mm to 1000 mm; the pipe material is concrete; and the mean slope is about 0.8%. The highest part of the area is in the middle of the catchment (Figure 1) with heights of up to 19 m.a.s.l. sloping down towards the north and south outlet (4 and 8 m.a.s.l. respectively). Time of concentration for the area at outlets is 50-60 min, but the critical durations (time since beginning of the rainfall when highest flow rate or volume is obtained at specific locations) for the different nodes in the system are shorter (15–30 min). The MikeShe model handles pervious area runoff using a 5 m*5 m grid of soil columns. Groundwater level is set 1 m below the surface, and groundwater movements have not been

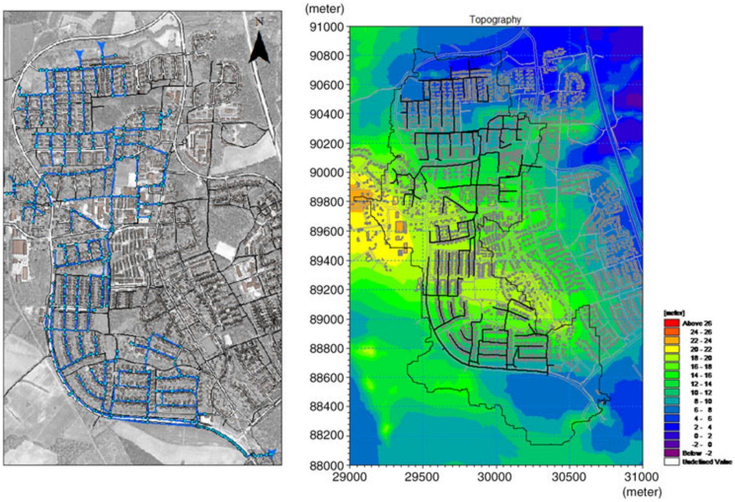

Figure 1. The Mouse hydraulic model, network of pipes and nodes (to the left). ©Lantmäteriet Gävle. Medgivande I 2001/0084. Topography and larger catchment (to the right).(DHI 2008).

addressed). The soil is defined as mostly Moraine, with uniform spatial properties, hydraulic conductivity of 0.018 m/h, and moisture content set at field capacity at the beginning of each rainfall event.

The two models interact at the gully pots (nodes in the Mouse model) where runoff from impervious surfaces (most of the roads, buildings, paved areas) as estimated by Mouse (using a time-area approach) is combined with pervious area input (calculated by MikeShe) and passed on to the Mouse network model. If water levels in the system exceed ground level (i.e. flooding), water from the Mouse model will be forced out from the nodes and routed or ponded on the surface (by MikeShe) until it can later re-enter the network at the same or another node.

2.2 *Rainfall input data - Design storms*

Design rainfalls are derived from the statistical rainfall intensity-duration-frequency (or return period) relationship for the specific location (known as IDF curves (Chow *et al.* 1988)). The relationship used here is from the latest Swedish national evaluation (Dahlström 2010) which is recommended by national guidelines (SWWA 2011) (Equation (1)). The formula is based on a cloud physical concept of the condensation process, which takes into account both convective rain clouds and less intense rain from frontal clouds (Dahlström 2010). The formula is recommended for return periods of 0.5 to 100 years (SWWA 2011). Although rainfalls of longer return periods (e.g. 100 years) are naturally rare in the rainfall statistics, which means that care needs to be taken in the interpretation of results.

$$i_F = \left(190 * \sqrt[3]{(F*12)} * \frac{\ln(T_r)}{T_r^{0.98}} + 2\right) * 0.36 \qquad (1)$$

Where i_F = Mean rainfall intensity (mm/h), F = Return period (years), T_r = Duration (min)

In this study two profiles are used: Block rainfall (e.g. Arnell 1982); and Chicago design storm (CDS, by Kiefer and Chu 1957). The Block rainfall intensities for durations 5-120 min (Table 1) were run in a time series to save simulation time and to identify critical durations within the system, as recommended by SWWA (2011).

Table 1. Block rainfall depths for each duration 5–120 min, and total volume.

Volume (mm)	5	10	15	20	30	40	50	60	90	120	Total Volume
Block 2y	5.5	8.0	9.6	10.7	12.3	13.5	14.5	15.3	17.3	18.8	125.6
Block 5y	7.5	10.9	12.9	14.4	16.6	18.2	19.5	20.6	23.1	25.0	168.7
Block 10y	9.4	13.7	16.3	18.1	20.8	22.8	24.4	25.7	28.8	31.1	211.1
Block 100y	20.2	29.3	34.8	38.8	44.5	48.6	51.8	54.6	60.7	65.3	448.6

The time series includes 24 h gaps between the blocks, so that the responses should not interfere with each other. Using design storms including all relevant storm durations for a system is also used by e.g. Tait *et al.* (2008) and Kellagher (2009). The CDS rainfall, where mean intensities for shorter durations are nested within the longer duration intensities (with a skewness factor of 0.37 at the peak) is the most commonly used design rainfall in Sweden. Total duration 120 min. Return periods of 2, 5, 10 and 100 years have been used.

2.3 *Rainfall input data - Observed rainfall*

From 1991 to 2004, rainfall for the study area was measured using a 0.2 mm tipping bucket gauge. About 700 rainfall events have been identified by Hernebring (2006) using a time between events of 2 h and excluding rainfalls of less than 0.2 mm of volume and 0.1 mm/h of intensity. From this set of data maximum intensities for durations from 5–120 min were obtained and statistically evaluated (Hernebring 2006). Selections of rainfall in this study were based on the associated return period for each duration (5–120 min), as well as the average of the durations 5–60 min (related to time of concentration 60 min). Return periods related to the Swedish national rainfall statistics (in Equation (1) (Dahlström 2010)). Initially fourteen events were modelled in this study, each having a return period of more than one year (at any duration 5–120 min). However, as most of these caused no flood problems, results for only the five events with return periods of two years or more are discussed here, which is a similar procedure as used e.g. in Kellagher (2009). Event durations, volumes and maximum intensities are shown in Table 2. The events in 1994-09-09, 1996-06-19 and 2002-07-24 correspond to about a 2 year return period, the 1997-07-27 event to about 5 years and the 2003-07-29 event to about 100 years. The specific profiles of these rainfalls are shown in Figure 2.

2.4 *Climate change and climate factors*

Kalmar has a yearly average temperature of 7 °C (16 °C in July and −2 °C in January) and precipitation of 484 mm, with highest intensity rainfalls occurring in the summer. Future climate is expected to increase yearly temperature by about 4–5 °C and yearly precipitation by about 10–20%, though summer rainfall is expected to decrease by 10–40% (RCA3, SRES Scenarios A2, B2, in Kjellström *et al.* (2009)) – due to fewer storms as rainfall intensities are expected to increase (Olsson *et al.* 2009). The study catchment is 2 km from the Baltic sea, and more than 4 m above sea level at its lowest point, thus rising sea level is not a major concern. Future temperatures will influence the evapotranspiration (about 0–10% for the summer season, Kjellström *et al.* 2009) and thus affect soil water content and runoff generation. Permeable areas account for a large part of the studied catchment, although the influence on runoff entering the urban drainage system is relatively small (see also Section 3.1). Setting initial soil water content to the recommended field capacity (a fully drained condition) effectively ignores any further drying by evapotranspiration. Future soil water content, particularly in summer, is likely to be dryer and thus offset in part any impacts due to increased rainfall intensity.

Two approaches have been used in defining factors to adjust storm rainfall for climate change: (1) a constant adjustment factor applied to the entire rainfall (single event rainfall), according to Swedish national recommendations by the SWWA (2011); and (2) a Delta Change approach, where the adjustment factor varies as rainfall intensity changes (between and during storms), and where the relationship between adjustment factor and rainfall intensity changes with different season (see Olsson *et al.* 2009). The Delta Change factors (depending on intensity and season) are applied to the observed rainfall record (full time series) from which the most intense single event rainfalls were selected for the model runs in this paper.

The constant climate factors are based on the Swedish national recommendations for urban drainage, and calculated as averages for five regions in Sweden for the future period 2071-2100 (SWWA 2011). They are based on regional model RCAO (and two global circulation models: ECHAM4/OPYC3, HadAM3H) and two emission scenarios SRES A2, and B2 (Nakicenovic *et al.* 2000). For the Kalmar region climate factors of 1.1–1.2 is

Table 2. Characteristics of the five most intense rainfall events in the Kalmar rainfall time series (1991–2004), with return period of about two year or more.

				Durations (5-120 min) associated with Return period (years)									
	T_{tot} [h]	P_{tot} [mm]	F_{avg} [y]	5 [y]	10 [y]	15 [y]	20 [y]	30 [y]	40 [y]	50 [y]	60 [y]	90 [y]	120 [y]
1994-09-09	8.08	27.6	2.0	0.7	1.3	1.8	2.3	2.5	2.7	2.2	2.3	2.2	2.1
1996-06-19	2.01	12.8	2.0	4.2	2.9	2.5	2.0	1.4	1.2	1.0	0.8	0.7	0.6
1997-07-27	2.32	15.4	5.4	13.1	8.1	6.2	5.3	3.7	2.8	2.2	1.9	1.3	1.0
2002-07-24	0.87	12.0	2.1	2.0	3.6	3.2	2.6	1.8	1.3	1.1	0.9	0.6	0.5
2003-07-29	6.98	93.0	90.1	21.4	43.5	59.4	62.8	81.0	124.4	157.4	171.2	144.2	125.8

Note: T_{tot} - total duration, P_{tot} – total volume, F_{avg} - average return period (5-60 min)

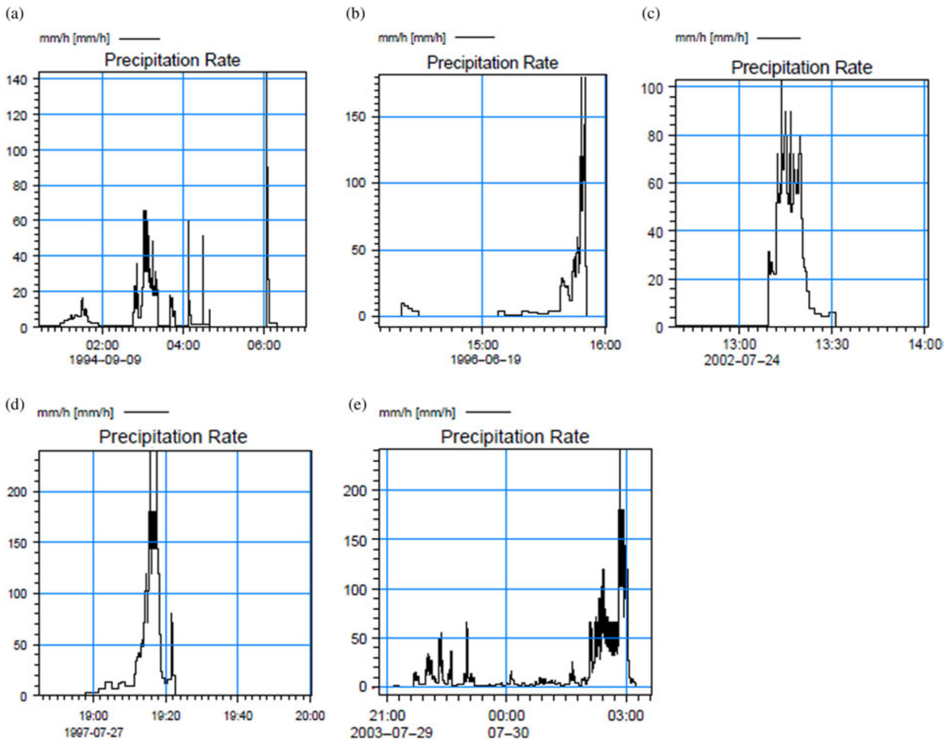

Figure 2. Rainfall profiles for the five most intense rainfall events in Kalmar (1991–2004); a) 1994-09-09, b) 1996-06-19, c) 2002-07-24, d) 1997-07-27, e) 2003-07-29.

recommended (SWWA 2011), and for this paper the higher climate factor (CF: 1.2) is chosen.

For the Delta Change approach (Olsson *et al.* 2009), climate model data were derived from the regional climate model RCA3 by Rossby Centre (Kjellström *et al.* 2005, based on global model ECHAM4/OPYC3) with a resolution of 30 min and 50*50 km grid sizes and the future global emission scenario SRES A2 (defined by Nakicenovic *et al.* 2000). The main assumption with the method is that the same differences detected in the climate model data (areal rainfall in this case) for the control and future period also occurs in the observed data set (point rainfall). Climate model outputs for control (1971–2000) and future period (2071–2100) were divided into seasons (spring, summer, autumn), and within each subset, the 30 min intensities were ranked in percentage classes, from which a series of DC factors relating the x% intensity for control and future periods could be derived. These factors were then applied by (i) dividing the observed time series (Kalmar tipping bucket time series 1991–2004) into seasons and aggregating rainfall into 30-min intervals (to be compatible to climate model data), and (ii) ranking the 30-min intensities into percentage classes, to which the corresponding DC factors might be applied. In practice, the factors have been applied to the rain gauge bucket size during the corresponding 30 min interval, so that rainfall data can be abstracted at the "time between tips" intervals present in the observed data series. It should be noted that varying DC factors will be applied to storms extending over several 30 min intervals with changes in rainfall intensity. Factors applied on the most intense single event rainfalls used in this study (selected from the time series on which the DC-factors were applied) are presented in Table 3.

2.5 *Input rainfall characteristics*

The studied rainfalls and their characteristics, with and without climate change factors, are shown in Table 4. The Block rainfalls are shown for the 30 min duration, as an

Table 3. Kalmar area climate factors: Constant factors (CF1.2) for all rainfalls and Delta Change factors (CFDC) for specific rainfall events.

Rainfall		Min	Max	Period
Block, CDS, Obs	CF1.2	1.2	1.2	All seasons
19940909	CFDC	1.11	1.82	Autumn
19960619	CFDC	0.65	1.21	Summer
19970727	CFDC	0.65	1.18	“
20020724	CFDC	0.65	1.17	“
20030729	CFDC	0.65	1.27	“

example (see also Table 1). Applying a climate factor as a constant uplift of 1.2 (CF 1.2) will increase both volume and intensity whereas the Delta Change factors (CF:DC) will give different increases in volume and maximum intensity (Table 4).

2.6 *Model simulations and evaluation criteria*

Most previous comparisons of modelled catchment response to design storms and observed rainfall events have focussed on peak flows for specific locations within the system, often the outlet (e.g. Kiefer and Chu 1957, Packman and Kidd 1980, Arnell 1982, Beaudoin *et al.* 1983, Niemczynowicz 1989). Some later studies also used peak flow criteria (e.g. Waters *et al.* 2003, Denault *et al.* 2006, Semadeni-Davies *et al.* 2008). But with practitioner and public focus moving from design of systems more towards performance of systems and as simulation models have developed, the dynamics of water on urban surfaces and whether surface flooding occurs has become more important.

In this study flow rates are presented in a few cases for comparison, but a wider range of response criteria have also been used, e.g. water levels in nodes related to the ground level and critical levels within the system (as suggested by Berggren *et al.* 2012), but also addressing more directly the occurrence and extent of flooding by using threshold levels above ground. This approach allows for a more detailed assessment of differences in response between different rainfalls. These criteria include:

(1) Numbers of nodes in the system where maximum water level in an event exceeds each of two threshold levels (ground level, GL, and critical level, CL, of 0.5 m below ground level). The two thresholds help to indicate the safety margin in the system. Peak flows for the main outlet are also studied as a comparison.
(2) Mean and standard deviation of differences in maximum water level across all system nodes for different rainfall inputs, allowing the use of a t-test to assess the significance of differences at the 95% level. The test t_0 value in this case is $t_{0.025,439} = 1.960$ (Montgomery 2001). Also peak flows for all pipes in the system have been studied as a comparison. The results for (1) and (2) are taken from the Mouse model outputs.
(3) Maximum flooded area, assessed at three threshold levels: 0.05 m, 0.10 m and 0.15 m above ground level – the latter chosen to represent when surface water starts to impact on buildings and property. Flooded areas are assessed from the MikeShe model outputs, counting the grid cells with maximum water depths above the threshold levels and rescaling by the 25 m^2 grid size.

Table 4. Input rainfall characteristics

			-		CF: 1.2		CF: DC	
Rainfall	F* (y)	T_{tot} (min)	P_{tot} (mm)	I_{max} (mm/h)	P_{tot} (mm)	I_{max} (mm/h)	P_{tot} (mm)	I_{max} (mm/h)
Block	2	30**	12	25	15	30		
Block	5	30**	17	33	20	40		
Block	10	30**	21	42	25	50		
Block	100	30**	44	89	53	107		
CDS	2	120	19	66	23	80		
CDS	5	120	25	90	30	108		
CDS	10	120	32	113	38	135		
CDS	100	120	66	242	79	291		
1994-09-09	2	485	27	144	33	173	41	183
1996-06-19	2	121	13	180	15	216	14	218
1997-07-27	5	139	15	240	19	288	18	283
2002-07-24	2	52	12	103	14	123	14	121
2003-07-29	100	419	96	240	115	288	109	305

Note: F* – Return period, specific for design storms and equivalent for observed. 30** - 30 min duration Block shown as an example T_{tot} – Duration. P_{tot} – Volume. I_{max} – Maximum intensity. CF – climate factor. 5–120* - Blocks in a sequence of durations 5, 10, 15, 20, 30, 40, 50, 60, 90 and 120 min.

3. Results and discussion

3.1 Modelled water levels at nodes and on catchment surface

The numbers of flooded nodes (maximum water level in nodes exceeding ground level) resulting from different rainfall inputs are presented in Table 5. The peak flows at the system main outlet are also shown for comparison. Both evaluation criteria show similar patterns, but the number of affected nodes gives a better indication of system capacity and possible impacts on the urban area. There is an obvious increase in response with increasing return period, and response levels are similar for different rainfalls that are of similar return period. As expected from previous research (e.g. Arnell 1982), the CDS rainfalls give higher peak flows, and more flooded nodes than the Block rainfalls. The return period assigned to the observed rainfalls corresponds well with the design rainfalls of the same return period, on the number of flooded nodes as well as peak flow.

To address in more detail the safety margin of the system as well as the extent of flooding, the maximum water level in nodes and the maximum flooded area are shown related to threshold levels both within the system and on the surfaces (Table 6). The results are presented as a percentage of the total number of nodes (440) and the total catchment size (22.7 km^2). Low return period rainfall (2 year Block, CDS and observed rainfalls 1994-09-09, 1996-06-19, and 2002-07-24), prior to climate change, shows few flooded nodes and little flooded area. For larger rainfall events (100 year Block, CDS and observed rainfall 2003-07-29) the safety margin of the system is very low – the majority of nodes in the system are affected by higher water levels (69%, 74% and 72%) even though less than half of all the nodes actually flood. When adding the climate factor the safety margin decreases further.

The permeable area contribution to total runoff volume depends on the duration and volume of rainfall, but investigations in this catchment found the impact was small. Additional runoff volume was 0.9–3.9% for rainfalls of return period 2, 5 and 10 years (highest for Block rainfalls), though greater volumes (about 15%) were found for longer return periods (100 years). Climate factors increase runoff volumes by similar amounts, but the total contribution from permeable areas remains low. However, further research in this field is needed, as urban permeable areas are central to new runoff management thinking, such as e.g. Green Infrastructure (GI), Best Management Practice (BMPs), Sustainable drainage systems (SuDS) and Low Impact Development (LID) (e.g. Gersonius *et al.* 2012), and considered important when adapting urban areas to become more resilient to future changes in runoff.

3.2 Flood response for CDS and Block rainfall inputs

CDS rainfall causes higher water levels in the storm water system than Block rainfall for return periods 2, 5, 10 and 100 years (Tables 5 and 6). More detailed differences between CDS and Block rainfall impacts are shown in Table 7 as the mean difference, standard deviation, confidence interval and the t-value for both peak flow (in all pipes) and maximum water level (in all nodes). Note that for Block rainfalls the maximum peak flow and maximum water levels at nodes can result from different Block durations. Upstream Nodes in the system are in general more affected by rainfall of high intensity, whereas for nodes further downstream (closer to the outlet) the rainfall volume is more critical. It should also be recognized that, using CDS rainfall, upstream surcharging may restrict onward flow rates such that downstream surcharging does not occur, but using Block

Table 5. Number of flooded nodes and peak flow (at main outlet) with different rainfall inputs.

		Peak flow [m^3/s]			Floodednodes [-]		
	F* [y]	-	CF:1.2	CF: DC	-	CF:1.2	CF: DC
Block	2	1.51	1.65		1	2	
Block	5	1.75	1.90		3	17	
Block[1]	10	1.94	2.08		22	45	
Block[1]	100	2.34	2.37		185	215	
CDS	2	1.65	1.80		2	7	
CDS	5	1.89	2.04		15	28	
CDS[1]	10	2.06	2.17		35	61	
CDS[1]	100	2.35	2.41		202	246	
1994-09-09	2	1.66	1.82	2.11	2	9	40
1996-06-19	2	1.57	1.72	1.69	2	7	6
1997-07-27	5	1.84	1.99	2.03	18	35	32
2002-07-24	2	1.61	1.77	1.82	3	10	8
2003-07-29[1]	100	2.36	2.43	2.48	194	241	253

Note: F* – Return period, specific for design storms and equivalent for observed. [1]- Partly surcharged system for longer return periods (10, 100 years), which may affect especially peak flow rates.

Table 6. Nodes affected by flooding (> GL) and exceeded critical levels (> CL), and Flooded area evaluated for three threshold levels (L) above ground. Total of nodes: 440, Total area: 22.7 km^2.

			Nodes affected (%)		Flooded area (%)		
Rainfall	F* [y]	CF	GL: 0.0 m	CL: −0.5 m	L: 0.05 m	L: 0.10 m	L: 0.15 m
Block	2	-	0.2	2.5	0.0	0.0	0.0
Block	5	-	0.7	8.2	0.3	0.0	0.0
Block	10	-	5.0	17.7	0.9	0.2	0.1
Block	100	-	42.0	68.9	20.2	6.8	2.5
Block	2	1.2	0.5	4.1	0.1	0.0	0.0
Block	5	1.2	3.9	16.4	0.7	0.1	0.0
Block	10	1.2	10.2	24.8	2.5	0.4	0.2
Block	100	1.2	48.9	75.7	28.7	12.5	6.4
CDS	2	-	0.5	3.6	0.1	0.0	0.0
CDS	5	-	3.4	14.8	0.5	0.1	0.0
CDS	10	-	8.0	22.7	1.8	0.3	0.1
CDS	100	-	45.9	73.6	24.9	10.5	5.1
CDS	2	1.2	1.6	10.7	0.3	0.0	0.0
CDS	5	1.2	6.4	20.2	0.1	0.3	0.1
CDS	10	1.2	13.9	33.4	4.5	0.8	0.3
CDS	100	1.2	55.9	78.4	33.3	15.6	9.6
1994-09-09	2	-	0.5	3.9	0.1	0.0	0.0
1996-06-19	2	-	0.5	4.3	0.0	0.0	0.0
1997-07-27	5	-	4.1	15.2	0.5	0.1	0.0
2002-07-24	2	-	0.7	4.5	0.1	0.0	0.0
2003-07-29	100	-	44.1	72.0	27.3	12.2	6.4
1994-09-09	2	1.2	2.0	9.3	0.3	0.0	0.0
1996-06-19	2	1.2	1.6	8.0	0.2	0.0	0.0
1997-07-27	5	1.2	8.0	22.0	1.2	0.2	0.1
2002-07-24	2	1.2	2.3	11.8	0.4	0.1	0.0
2003-07-29	100	1.2	54.8	78.4	35.7	17.2	11.4
1994-09-09	2	DC	9.1	23.0	2.4	0.4	0.2
1996-06-19	2	DC	1.4	8.4	0.2	0.0	0.0
1997-07-27	5	DC	7.3	21.6	1.1	0.2	0.1
2002-07-24	2	DC	1.8	10.7	0.3	0.0	0.0
2003-07-29	100	DC	57.5	80.5	37.8	18.6	12.4

Note: F* – Return period, specific for design storms and equivalent for observed.

rainfalls of different durations, surcharging may be found both upstream and downstream.

The statistically significant increase in maximum water levels at nodes between CDS and Block rainfall is consistent with previous research (Arnell 1982). The difference increases with return period until the system becomes severely overloaded, and flood water spreads over the land surface (as with the 100 year event). For flow

Table 7. Differences between CDS and Block rainfall for peak flow in pipes and maximum water levels in nodes, using a statistical paired nodes comparison t-test.

		Flow rates				Max water level			
(vs Block)	F [y]	MV [m^3/s]	σ [m^3/s]	CI [m^3/s]	T-value [-]	MV [m]	σ [m]	CI [m]	T-value [-]
CDS	2	0.01	0.03	(0.00; 0.01)	5.58	0.10	0.16	(0.08; 0.12)	13.4
CDS	5	0.00	0.03	(−0.01; 0.00)	−2.17	0.15	0.17	(0.13; 0.17)	17.8
CDS[1]	10	−0.01	0.04	(−0.01; 0.00)	−5.50	0.17	0.19	(0.14; 0.19)	18.7
CDS[1,2]	100	−0.03	0.06	(−0.04; −0.03)	−18.24	0.05	0.09	(0.04; 0.07)	12.2

Note: [1]Partly surcharged system (more for CDS), which may affect especially the resulting flow rates. [2]Many flooded nodes will affect the resulting max water levels in the nodes, as the level will be measured above ground.

rates, however, CDS shows an increase only for the lowest return period rainfall event (2 year). This is probably due to the increased number of surcharged pipes for CDS rainfall simulations compared to simulations with Block rainfall. Thus, using progressive changes in peak flow within the system as comparison criteria is only reliable if the system is not heavily surcharged.

A Block rainfall can be used to identify critical durations within the system, related to specific nodes. The total time of concentration at the main outlet in the Kalmar stormwater system is some 60 min, but using Block rainfalls of various durations (5–120 min) in sequence found shorter critical durations (reflected as flooded nodes) for major sub-parts of the system (about 15–30 min) (Table 8). This information can be useful when investigating possible adaptation actions in the area, combining information on safety margin (e.g. exceeding threshold levels) and critical duration at nodes. A short critical duration (near the top of the system) may need more focus on decreasing peak flows, while a longer critical duration (closer to the outlet) might need more focus on decreasing total volumes. Adaptation actions can be performed either within the (piped) system, or dealing with the urban area. This area of research does however need further studies, related to e.g. possible adaptation actions and their possibility of reducing peak flow and volume of runoff.

3.3 Flood response for observed and design rainfalls

It is common practice to assume that the response in the urban drainage system using design rainfall of a specified return period is similar to the flooding return period. The return period of different parts of the observed rainfall, however, correspond to a variety of return periods, not a specific one as with the design rainfall. Comparing the five selected observed rainfalls with design rainfalls of the same (assigned) return period shows very similar flooding response - considering the number of affected nodes and peak flow at the outlet (Tables 5 and 6) as well as the maximum flooded area (Table 6). The paired nodes comparison of water levels showed that observed rainfall of a 2 year return period (rainfalls 1994-09-09, 1996-06-19, and 2002-07-24) compared to the design storms, are higher than the Block rainfall both for the observed storms individually and average for the three storms (not shown in detail). The maximum water level response from CDS rainfall was higher or equal to the observed storms (of 2 year return period). The average water levels from all three observed storms showed no difference compared to CDS. Thus the results indicate that selecting observed rainfalls based on a return period criteria, as in this study, may give responses more similar to the CDS rainfalls than the Block rainfalls. This is probably due to both CDS and observed events having a hyetograph design with one or more peaks instead of average intensity hyetograph as the Block rainfalls.

Comparing the response in specific manholes/nodes in the system, Block rainfall response was also much lower than the CDS and Observed rainfalls (of the same assigned overall return period). The observed rainfall yielded flooding (i.e. maximum water level exceeding ground level, GL) at the same nodes in the system as the CDS rainfall. Similar results were found for the threshold level −0.5 m below ground, but these are not discussed here in detail. These results imply that, within the general confidence in current rainfall climates, using observed or design rainfalls give good agreement in maximum levels in the system. Thus, this work supports the use of an appropriate selection of observed rainfall events instead of design storms to study the system capacity, which in turn facilitates the use of climate change methods applying diversified climate factors on the full time series, e.g. Delta Change.

3.4 Impact of climate factors

The use of constant or Delta Change climate factors gives different responses in the system and on the urban surfaces. Previous research showed that, due to thresholds within the system, impacts (e.g. on flood levels) could be greater than the applied climate factor (Niemczynowicz 1989). The impact pattern in this case study is similar for all threshold levels, comparing number of affected nodes for current conditions with added climate factors of both constant (CF:1.2) and Delta Change (CF:DC) approaches (Table 6). The DC factor uplifts show a more varying impact pattern and especially the event 1994-09-09 stands

Table 8. Critical durations in flooded nodes, related to number of flooded manholes/nodes as a result of running Block rainfalls of different durations in a sequence.

Block duration	5	10	15	20	30	40	50	60	90	120 (min)	Tot (nodes)
Block 2y	1										1
Block 5y	1	1			1						3
Block 10y	1	4	5	6	5	1					22
Block 100y	5	29	44	40	34	23	0	7	2	1	185

out. This is, however, the only autumn event and thus adjusted using a different DC factor distribution than the summer events.

Peak flow responses as well as the number of flooded nodes were found to increase similarly, both using a constant climate factor (CF:1.2) and the variable Delta Change factors (CF:DC) (Table 7). The constant factor was below the maximum, but within the range of all, Delta Change summer factors for the highest intensity rainfalls, (CF:1.2 vs the CF:DC range of 0.65–1.27). The dynamic response of the affected nodes related to the maximum water level is however not the case for the major event in 2003-07-29, or the Autumn event in 1994-09-09. These results indicate a high dependence on the hydraulic response, due to the level of the maximum factor applied on the rainfalls (both the autumn event in 1994-09-09 and the summer event 2003-07-29 had higher maximum factors than the average of 1.2).

The differences between Block and CDS type of rainfall (using a paired nodes statistical evaluation) showed that the water levels in this system were 0.14–0.19 m higher for a CDS rainfall input, than for the Block type of rainfall. The corresponding numbers of flooded nodes were 60% higher (22 vs 35 nodes) for CDS. After applying a climate factor (CF 1.2) the difference between response from the CDS and Block rainfall increased further, although the relative difference in number of flooded nodes reduced, 35% (45 vs 61 nodes). Thus, depending on the safety margin in the system, the difference in actual numbers of flooded nodes can vary by more than the difference in maximum water levels. The added climate factor (CF 1.2) will increase the maximum water levels more for the CDS rainfall compared with the Block rainfall. Future CDS gave 0.27–0.33 m higher levels than today's CDS rainfall and for Block water levels in the future were 0.20–0.25 m higher. The difference between Block and CDS was less than the difference due to added climate factor of 1.2 (e.g. shown in Figure 3). The maximum water levels in nodes reflect the sensitivity of the system due to both the use of different types of rainfalls as well as climate change (on the rainfall characteristics) when related both to the ground level and the threshold level (addressing the safety margin).

Care must however be taken using either a constant or Delta Change factors, as there are limitations in both approaches. Uplift factors are often focused on changes in the intensity of rainfalls, but will change both the intensity and the volume (example in Table 4). A constant factor will increase both as much, which may not be in line with seasonal changes of the volume (as noted in Olsson *et al.* 2009). For the Delta Change approach (Olsson *et al.* 2009) both changes in intensity and total volume for each season is taken into account when applying diversified factors on the full time series. The profiles of the rainfalls may however be slightly modified. Further research is suggested related to these issues, addressing what influence increased intensity and volume may have and especially when using a time series approach.

3.5 General recommendations

Based on this study some general recommendations can be made, pointing to the choice of rainfall used when assessing hydraulic impacts on an urban drainage system. In Table 9 Block, CDS and observed rainfall events are

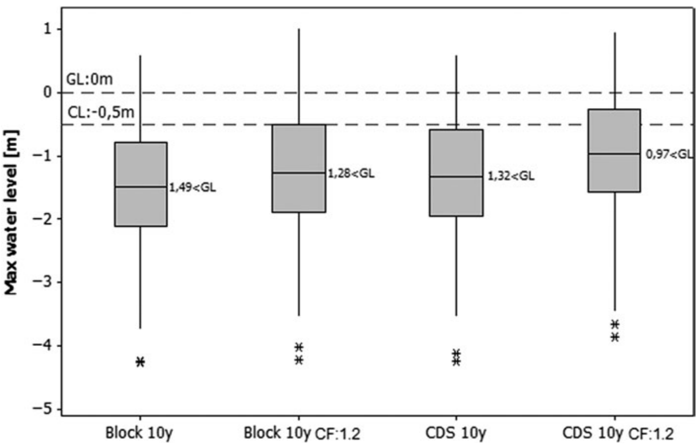

Figure 3. Response in the system as Maximum water levels in nodes, for Block and CDS rainfalls of 10 year return period, as well as added climate factors (CF 1.2).

Table 9. General recommendations on the use of rainfall as input to an urban drainage model and the climate factor method used. SE – Single event rainfall, TS – Time series rainfall.

Rainfall	Comments
SE: Block	• Lower impacts on the hydraulic performance of a system compared to CDS. • Specific critical durations throughout the system can be identified, and in relation to the safety margin in the system, useful information for the choice of adaptation action may be provided (e.g. if main issue is peak or volume). • Computer simulation run times may increase if time between events needs to be added so that the Block rainfalls (run in a sequence) does not interact. • Constant climate factor can be applied.
SE: CDS	• Higher impacts on the hydraulic performance on a system compared to Block. • If assessment is related to the maximum impacts on the urban drainage system and area, CDS rainfall is a preferable choice over Block rainfall. • Critical durations are taken into account within the CDS rainfall profile, although cannot be specifically identified. • Relatively short simulation computer run times. • Constant climate factor can be applied.
SE: Obs (selected from TS)	• Similar response as the CDS rainfall on hydraulic performance (for this case study using a return period based selection of observed single event rainfalls). • Constant climate factor can be applied. • Delta Change methods with diversified factors added to a rainfall time series can be applied, taking into account changes of both intensity and volume.

listed and the general conclusions made based on this study are summarized.

4. Conclusions

This paper presents results from using a Mouse/MikeShe (1D/2D) urban drainage model to assess flood response from design and observed rainfalls for a catchment in Kalmar, south east of Sweden, under current conditions and with adjustments to rainfall inputs for climate change. The design rainfall used includes the Swedish standard approach using a sequence of Block rainfall and Chicago design storms (CDS). Rainfall return periods covered 2, 5, 10 and 100 years. Methods used for future climate adjustment were: constant uplift (1.2) according current recommendations (SWWA 2011) and a Delta Change (DC) method (Olsson *et al.* 2009). In Table 9 recommendations are presented on the use of Block, CDS and observed single rainfall events. Summarized, the conclusions are:

- Depending on the purpose of the study, Block or CDS rainfall can be used. Block rainfall addresses more specifically critical durations in each point of the system (adding knowledge to the choice of adaptation action needed), whereas CDS points out the maximum hydraulic impact on the urban drainage system and urban area more explicitly.
- Observed rainfall events selected with a return period approach from a rainfall time series gave similar responses as for the CDS rainfalls for the same assigned return period, thus emphasizing the potential of using observed rainfall as a complement in capacity assessments – and a climate change method addressing differences in both intensity and volume (e.g. Delta Change method).
- Adding a constant uplift to a single rainfall event provides information about the sensitivity and the capacity of the system. The intensity and volume are, however, increased similarly, thus future seasonal changes in a time series may not be well described.
- Evaluating hydraulic response in an urban drainage system with different criteria may give different views of the situation. Comparing maximum water levels in the system (which also can be related to the safety margin) points out differences in hydraulic performance more clearly than addressing peak flow rates (either within the system or at the outlet) when the system is surcharged.

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Paper V

Indicators for urban drainage system: assessment of climate change impacts

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Indicators for urban drainage system -assessment of climate change impacts

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ABSTRACT

Changes of the climatic conditions will affect urban drainage systems, as they are closely related to the weather phenomenon and are built as to cope with the weather occurring. The aim of this paper is to investigate indicators that can be used to describe and compare impacts and adaptation measures in existing urban drainage systems. Problems in the system due to climate change can be summarised as problems with flooding of surfaces and basements, increased amount of combined sewer overflows (CSO), increase of the inflow to waste water treatment plants (WWTP) and increase in pollutants spreading from urban areas to the environment. The impacts needs to be described with indicators taking into account the system behaviour both before, during and after an event (e.g. urban flooding) has occurred, and can be divided into (A) description of the system performance, (B) capacity exceeding in the system, and (C) description of consequences as a result of capacity exceeding. The consequences can be divided into sustainable aspects as: technical, economical, socio-cultural, environmental, and health. The research is performed within a project which will also include model simulations of urban drainage systems in four Swedish municipalities as to assess impacts and evaluate the use of indicators.

KEYWORDS

Climate change; impacts; indicators; urban drainage systems;

INTRODUCTION

Changes in the climatic conditions (IPCC, 2007) will affect infrastructure in cities and the vulnerability of the society increases also as urbanisation continues and population grows. Urban drainage systems are closely related to weather phenomenon, and when these events might change as a consequence of global warming, the risk of problem in the system or related to the system increases. In order to cope with future climate change, it is necessary to consider both mitigation actions and adaptation (Stern Report, 2006) and also about how to identify risks and vulnerability in our societies. For urban drainage systems, the adaptation actions are most evident, but these actions should however be taken with the mitigation issues in mind. The adaptation actions should be able to cope with changes for a long period of time, since the life-length of pipes can be up to 100 years, or more. In such a long time, there are many things that can change. The solutions or measures for adaptation should therefore be robust and able to cope with a variety of future changes.

Climate impacts on urban drainage systems has been studied previously, (e.g. Waters *et al.,* 2003; Ashley *et al.,* 2005; Semadeni-Davies *et al.,* 2005; Denault *et al.,* 2006), and can be summarised as problems with flooding of surfaces and basements, increased amount of combined sewer overflows (CSO), increase of the inflow to waste water treatment plants (WWTP) and increase in pollutants spreading from urban areas to the environment. These impacts are described often in a traditional way, where system performance is assessed and interpreted regarding consequences for the system and the city. Rainfall intensity and amount is the problem which has had the most attention so far, due to the often rapid runoff situation in urban environment. When addressing impacts of a changing climate, there is always the question how to describe these impacts and risks in a good way. Are there indicators which make it possible or easier to describe and compare impacts in different parts of an existing system? And can these parameters or indicators which are used for the impact assessment also be of use for the evaluation and prioritising between adaptation actions, and between different areas of the city? Is it also possible to find out how sensitive an urban drainage system is, before any consequences are registered? And if there is impacts, and damage (e.g. surface flooding, basement flooding etc) can these be described and evaluated from sustainability point of view (technical, environmental, socio-cultural, health and economy)? When changes are to be planned for an urban drainage system, these aspects are important to involve. Palme (2007) describes how indicators can be used in order to assess the sustainability of urban water systems, which are valuable information but in general too coarse to be used for the purpose of climate change impact assessment. There is a need of more detailed and specified indicators for this purpose.

The aim of this paper is to investigate possible indicators which can be of use when describing and comparing impacts of climate change on urban drainage systems. The paper is a part of a project where four municipalities in Sweden are involved, and case studies in these municipalities will further on support the evaluation and assessment of indicators, and also their capacity to describe the effect of different adaptation measures.

METHODS

The project consists of two parts, literature study of the indicators and a first classification of their character, and the model simulation part with case studies and tests of the indicators. The second part is not finished at the time of writing but preliminary results from this part will be presented at the time of the conference.

The first part of this paper is literature review, of both urban drainage impacts due to climate change, and of indicators, starting with sustainable development criteria. Then a classification of the indicators found in literature, and indicators suggested in this paper, according to their purpose, what they describe, and their character.

In a continuation, the suggested indicators are to be tested in case studies in four municipalities in Sweden, within a newly started project. From each municipality, two catchment areas are to be modelled, and with help from these model simulations evaluation of the indicator is to be performed in collaboration with representatives from each municipality.

In figure 1, the framework of the project is described. Input for the simulations of urban drainage models are climate parameters (rainfall intensity, changes in temperature, sea levels, etc). Changes in the urban environment (urbanisation, changes of impervious areas, runoff characters) are to be held constant at first, and later on changed according to thoughts about development in the municipalities. Model simulations are to be performed and the results are to be evaluated with help from indicators. Adaptation measures are also to be suggested and tested for their impact on the system and how they react on climate changes.

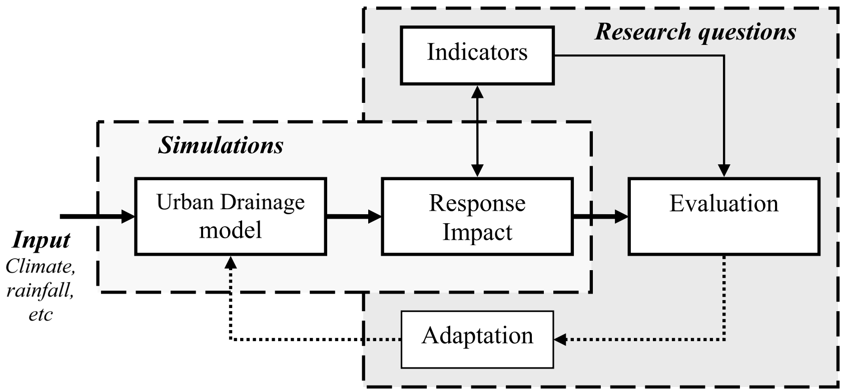

Figure 1. Framework for the project, model simulations and research environment with evaluation with help from indicators. Adaptation measures changes the urban drainage models and thus the results of the simulations.

RESULTS AND DISCUSSION

Urban drainage impacts due to climate change

There are some specific problems connected to this area, and the main issues are:

- The existing urban drainage system is designed to cope with the weather conditions for a specific area. The age of the system can vary and, in some parts, it can be very old, e.g. in many old city centres. This means that the existing urban drainage systems have been designed for the past climate conditions, but maybe not for the situation occurring today or for the future.
- Increase of population also affect the number of events causing damages, more people will be affected and are vulnerable to natural phenomena, such as heavy rainfall events, storms, flooding etc. Urbanization is also a major issue as the urban drainage system might have been constructed for a city whose impervious surface areas were fewer and smaller than those in today's cities or will be in tomorrow's cities. This will affect urban runoff.

- Several global climate models are available, and there are also different scenarios that affect the model results; together, these contribute to the many choices when choosing the input data for a research project. There are also large uncertainties involved in this field. Due to the spatial and temporal resolution of global climate model data, there is a problem connected with the use of rainfall for simulations or calculations of urban hydrology (urban runoff). Therefore, some dissaggregation or adaptation techniques of data are needed.

The assessment of climate impacts on urban drainage systems can be performed from different points of view. Berggren *et al.* (2007) suggested Urban Drainage Model Simulations, Geographical Information Systems (GIS) and Risk Analysis, as tools for the assessment of impacts. From earlier literature, the most common approach is urban drainage model simulations (e.g. Niemczynowicz, 1989; Waters *et al.,* 2003; Ashley *et al.,* 2005; Semadeni-Davies *et al.,* 2005; Denault *et al.,* 2006). GIS has also become more common, for example used as a complement to other tools in describing the impacts on a geographical scale.

Considering climate change, the most urgent problem for many cities is the intensification of the hydrological cycle with, for example, more intense rainfall and extreme weather events occurring. These events may cause e.g. flooding of surfaces and basements, combined sewer overflow, and also decreased flow capacity in the system due to increased amount of infiltration into pipes.

The different ways to handle climate model information for the use in urban drainage contexts can be described as *static, semi static* and *dynamic* (Berggren, 2007), according to the way information from climate models are used, from a fixed percentage of changes, a dynamic dissagregation, or something in between where climate model information is used but not directly in an urban model (e.g. delta change method, Olsson *et al*., 2006).

The typical problems in an urban drainage system can be intensified due to climate change, and more intense rainfall events. Urbanisation (more impervious surfaces in a city) has great impact on urban runoff and gives e.g. more rapid runoff and higher amounts of water in the systems (Waters *et al.,* 2003; Semadeni-Davies *et al.,* 2005; Denault *et al.,* 2006). Ashley *et al.* (2005) suggested that potential effects of climate change on urban property flooding are likely to be significant in the future. Infiltration into pipe systems increases as the precipitation increases in amount and in intensity (Niemczynowicz, 1989; Semadeni-Davies, 2004; Semadeni-Davies *et al.,* 2005), which will affect the inflow to the wastewater treatment plant, and facilities for treatment of storm water (BMPs), and can also decrease the capacity of the system, which makes it more probable to have flooding and combined sewer overflow during rainfall events. The impact on the system due to exfiltration and damage (also sediments) to pipes, and how this may change in the future, has not been found in the literature.

Regarding the impacts on receiving waters, Niemczynowicz (1989) showed potential environmental impacts due to an increased amount of pollutant released to receiving waters (suspended solids (SS), biological oxygen demand (BOD7), phosphorus, copper, zinc, and lead). Semadeni-Davies *et al.* (2005) showed that the total load of nitrogen released to receiving waters via overflow (CSOs) would increase in the future. And also Denault *et al.* (2006) found that the environmental impacts of climate change and urbanisation (increase of the impervious areas in the city) indicate a great vulnerability for the natural ecosystems of the receiving waters.

Climate change parameters

Since 1988, the UN's Intergovernmental Panel on Climate Change (IPCC) has worked to assess changes in the climate and gather the latest findings of researchers from all over the world in order to put together assessments of observed and expected changes in the climate. The first assessment report was published in 1990, and the latest during this year (2007), which is also the fourth assessment report (IPCC, 2007). The last twelve years (1992-2005) contained eleven of the warmest years since 1850, and the global mean temperature increased by 0,7 °C (±0,2°) during that time (IPCC, 2007). IPCC considers it very likely that the warming will continue in the 21st century, which will have an impact on, for example, precipitation patterns, snow cover, sea levels, and extreme weather events. For the northern hemisphere the warming is likely to continue in the 21st century, and is likely to be above the global mean. The changes in precipitation amount differ from area to area; in general, dry areas will become drier (e.g. Mediterranean) and wet areas wetter (e.g. north Europe). Intensity is likely to increase due to intensified hydrological cycle. Increases in the number of heat waves, heavy precipitation events, and total area affected by drought have been observed. Changes in storms (frequency, intensity etc) and small-scale severe weather phenomena have not been easy to estimate, due to e.g. the close relation to natural variations, and insufficient studies and measurements, but extreme weather events seems to become more often occurring in the future. (IPCC, 2007). These events will have impact on urban drainage systems.

Indicators

Palme (2007) presented indicators of use for the assessment of sustainability for urban water systems, from a whole systems approach. Usually, sustainability criteria are divided into different parts, reflecting the holistic view of the concept. Palme summarizes these as to hold either three, four or five dimensions, but also that the sustainability approach can be divided according to type of environmental-technical system. Hellström *et al.* (2000) describes criteria for sustainable urban water management as: Health and hygiene, social-cultural, environmental, economical, functional and technical. These criteria and indicators suggested in connection to this, are sometimes to coarse to be used when addressing impacts due to climate change on urban drainage systems, due to the need of rapid response on hydraulic behaviour. The indicators reflecting sustainability are however a good starting point, as the systems both should fulfil the sustainability criteria as well as to meet new climatic conditions in a good way.

Some of the functions of indicators is described in the document from UN (2007) on sustainable development indicators:

Indicators perform many functions. They can lead to better decisions and more effective actions by simplifying, clarifying and making aggregated information available to policy makers. They can help incorporate physical and social science knowledge into decision-making, and they can help measure and calibrate progress toward sustainable development goals. They can provide an early warning to prevent economic, social and environmental setbacks. They are also useful tools to communicate ideas, thoughts and values.

Some of these functions are also qualities wanted in indicators describing climate change impacts on urban drainage systems. Although, the indicators presented in this paper are of a different type in general and used on a more daily basis for example as decision support.

Classification

The classification follows the principle of: (A) description of the system performance, (B) capacity exceeding, and (C) description of consequences as a result of capacity exceeding. These can also be divided into how they are related to events occurring in the system, before any event has happen, during an event and after an event has occurred (Table 1). Events in these cases are e.g. heavy rainfall events that may cause flooding, snow melting in combination with rainfall, and more extreme weather events affecting the urban drainage system.

Table 1. Classes for indicators, based on when they are occurring, their character and how they are describing the events occurring in the urban drainage system.

	Before	While	After
System performance	A	-	-
Capacity exceeding	-	B	-
Consequences	-	-	C

Before an event has affected the systems and caused something to happen, it is important to evaluate the system performance, so that the daily function can be assessed. During an event, for example heavy rainfall occurring, the system will react on this and the capacity of the system needs to be evaluated. If the capacity (e.g. flow capacity) is exceeded then there will be consequences in the system and in the city (e.g. flooding of surfaces, flooding of basements, CSOs, etc) and these consequences can be divided or organised regarding their character after the event has occurred. The consequences can also be divided into subgroups according to the type: technical, economical, socio-cultural, environmental, and health, and also according to the persons and organizations affected. Examples of consequences:

Technical: Damage to pipes, facilities, pump stations, infrastructure, land (erosion and landslides), and property, which affects e.g. the system capacity, other parts of the technical infrastructure in the urban environment and inhabitants in the city.
Environmental: Spread of pollutants, nutrients, and hazardous substances in the water, soil, and/or air, affecting the ecosystems and species especially in the receiving waters.
Economical: cost of damage, cost of treatment of a polluted environment, and secondary costs, e.g. if people are hindered from doing their job due to infrastructure failure (roads, railways, internet, etc).
Socio-cultural: In the city/municipality/country, some areas might be more affected by damage and pollution than others, and if these are areas where poor people settle, then a class or social distinction will develop in the society.
Health: people become sick or are injured or killed by the damage and the polluted environment, and also in connection to drinking water quality.

In the literature found regarding impacts of climate change on urban drainage systems (e.g. Semadeni-Davies *et al.*, 2005; Ashley *et al.*, 2005; Waters *et al.*, 2003; Niemczynowicz, 1989), different indicators or parameters have been used to describe what is happening in the system. The indicators found in the literature together with some other examples of indicators has been summarized and divided into classes (Table 2), following the principle presented previously as A, B, C (Table 1).

In the list presented in Table 2, some indicators are missing. For example, pollutants and nutrients that affect the environment are not represented, nor is geographical distribution of a flood, which is important when describing consequences. There are also other characters that are important for an indicator describing climate impacts on urban drainage systems. They should for example:

- Easily describe hydraulic performance in the system (A, B)
- Give indications about how close to a consequence the system is, i.e. safety margin. (B)
- Make it possible to compare different catchment areas according to their sensitivity for climate change (B, C)
- Make it possible to compare different adaptation actions for the same catchment area, in order to decide what is best to do for this part of the system (B,C)
- Give indications about how adaptable, flexible and robust a system is (-)

Table 2. Examples of indicators used in literature in order to describe impacts of climate change on urban drainage systems, classified in group A, B or C. A: System performance, B: Capacity exceeding, and C: Consequences.

Type of system	Indicator	Unit	Ref.*	Classification
Combined system	CSO volume	[m3]	1, 2	B
	CSO frequency	[-]	-	B
	Pumping station overflow volume	[m3]	2	A
	Inflow to sewer system,	[m3]	1	A
	Inflow to WWTP	[m3]	2	A (B)
	Number of properties affected	[-]	3	C
	Economic loss due to damage	[EUR]	3	C
Separated system	Total flow volume	[m3]	2	A
	Total runoff volume	[m3]	4	A
	Time to peak discharge	[t]	4	B (A)
	Volume of peak discharge	[m3]	4	B (A)
	Number of pipes surcharged	[-]	4	B
	Frequency of flood	[m3]	-	B
	Duration of flood	[m3]	-	B
	Pipe flow ratio	[-]	-	B

*References, 1: Niemczynowicz (1989), 2: Semadeni-Davies *et al.* (2005), 3: Ashley *et al.* (2005), 4: Waters *et al.* (2003). CSO= combined sewer overflow, WWTP= Wastewater treatment plant

There is more work needed in order to find possible indicators, and they also need to be evaluated in case studies, regarding their sensitivity and to determine how well they describe impacts.

Case studies

In the Swedish project ("climate change and urban drainage") four municipalities (two from the south of Sweden and two from the north) are involved, and within this project study areas or catchment areas has been chosen as to represent problems occurring in the urban drainage system today, and what they will be in the future with a changing climate. These case studies are also to be used as to test the usability of the indicators suggested. Evaluation will also be performed of the indicators, what they are describing, and what the possibilities are to use them as decision support when addressing adaptation in the areas. The municipalities are Trelleborg (south of Sweden, at the coast), Borås (south of Sweden, inland), Sundsvall (north of Sweden, coast), and Skellefteå (north of Sweden, coast). The amounts of people living in these municipalities are 41 000, 100 000, 95 000 and 72 000 persons respectively.

CONCLUSIONS

There is a need of indicators that firmly and easily describes the impacts of climate change on urban drainage system. In this paper the classes A, B and C are suggested as tools for better understanding of indicators that can be used: (A) description of the system performance, (B) capacity exceeding in the system, and (C) description of consequences as a result of capacity exceeding. These can also be divided into how they are related to events occurring in the system, before any event (e.g. flooding) has occurred, during an event and after. The consequences can be divided into sustainable aspects as: technical, economical, socio-cultural, environmental, and health.

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Paper VI

Regional and seasonal variation in future climate: is green roof one solution?

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Regional and Seasonal Variations in Future Climate

Is Green Roof One Solution?

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Abstract
In this study, regional climate data was used to investigate the trend of changes for some climatic parameters, i.e. temperature, precipitation and maximum hourly precipitation in four different regions in Sweden. The general trend shows that Sweden will have warmer and wetter climatic conditions by 2100; however, the seasonal changes will affect the system differently, which makes them one of the main factors to be considered. The climatic data was used to determine the probable magnitude of changes by 2100 and to investigate the climate change impacts on urban drainage systems. The problems arising due to such changes were discussed regionally and seasonally and finally BMP methods, as an alternative way, to mitigate the climate change impacts were considered. As an example, green roof was applied to different urbanized conditions to estimate the approximate reduction of the extra water into the drainage system. As well as to investigate how much each of the BMP methods (green roof as an example for opening the further studies) could be useful for city planners towards more secure and sustainable cities in the future against the climate change.

Keywords: climate change data, regional, seasonal, precipitation, green roof, urban drainage

Introduction
Many studies have been performed related to climate change and there is still much to learn, such as the impact of climate change on urban areas. According to the Intergovernmental Panel on Climate Change (2007), the mean temperature has increased globally by 0.7ºC (±2.0ºC) in the past 100 years. The world has also experienced a decrease in snow and ice extent as well as a significant increase in precipitation since 1900 (McKibben, 2007). According to Mailhot *et al.* (2007) more energy has been brought by global warming to the hydrological system, which results in more active hydrological circulations. The climatic parameters will therefore most probably continue to change in the future.

The effects of climate change are not evenly distributed, which means that they are spatially and temporally different. For example annual precipitation for northern Europe is assessed to increase and the temperature increase is also estimated to be larger in winter. These changes are different for the Mediterranean region where the annual precipitation is decreasing and the maximum temperature is estimated to increase more in summer. A study made in Denmark (Mark *et al.*, 2008) showed more intensive rains during summer. In Sweden there would be more rainfall during autumn and winter while less in summer time. In Norway the largest increase of rainfall would be during autumn as well as in the number of intense rains. Since the annual mean temperature is increasing all over Europe, the snow period and depth are consequently decreasing, although the magnitudes of such changes would be different for different regions. (Solomon *et al.*, 2007).

Climate change could affect people's life directly. In urban regions where there are many impervious surfaces, some areas will encounter problems in their drainage systems due to the changes in precipitation. Surface flooding, surcharging sewers, combined sewer overflow and basement flooding are the problems which have already affected the urban areas (Nie *et al.*, 2009); such problems could also be amplified if the region is suffering from a fast urbanization and unsuitable drainage systems for future conditions. The flooding in 2000 and 2001 in Värmland and Västra Götland and the storm Gudrun in 2005 are examples of such problems in Sweden (Dotto *et al.*, 2007). An overview of changes shows a trend toward worsening urban drainage conditions; however, when it comes to making practical decisions by engineers and authorities, the important issue is how differently climate change could affect urban drainage systems locally and seasonally.

A number of studies have been made to investigate the probable future climate impacts on urban drainage systems. They all illustrated failure of the conventional systems due to such changes (Berggren 2007; Mark *et al.*, 2008; Watt *et al.*, 2003). The results show considerable impact on the systems. Nie *et al.* (2009), for example, estimated an 89% increase of CSO when the precipitation increased by 50% for Fredrikstad, Norway. For Helsingborg, Sweden, Semadani-Davies (2008a& b) estimated double CSO caused by only a 20% increase in precipitation.

The climate change impacts on the urban drainage, specifically storm water systems, will result in a larger volume of water in the system in a shorter time period, which will be caused by more precipitation and intense rains as well as a change of the snow melt pattern due to higher temperature. Besides the climatic variability and changes, other issues like urbanization and land-use changes must be taken into consideration. Therefore an analysis of the system integrated with all other involved factors seems necessary. To combine it with the sustainable development concept, an alternative solution to tackling climate change impacts on the drainage systems is the 'Best Management Practice' (BMP). BMP makes it possible to integrate the conventional drainage systems with alternative storm water drainage methods to mitigate the climate change impacts. Soak ways, swales, ponds, porous pavement infiltration trenches, water butts and green roofs are examples of the BMP approaches.

There are some estimations of the functionality of BMP in a number of articles (e.g. Butler and Davies, 2004; Berndtsson, 2010). For instance a 50-60% reduction could be achieved by combining grass swales and porous pavements (Bäckström, 2002). The BMP reductions in volume and peak flow depend on many factors, e.g. the climatic characteristics, the urban area conditions and their interactions and it is therefore site specific. The percentage of total volume reduction for green roofs, as an example, is different in different regions and seasons. In Germany the annual reduction of the total precipitation is estimated to be between 27% and 81% depending on where the green roof is implemented (Mentens *et al.*, 2006). Studies made in southern Sweden also illustrated the seasonal variation of the green roof functionality. (Bengtsson *et al.*, 2005).

Considering the problems caused by climate change and also the necessity of more research to mitigate such effects on urban areas for safer and more secure conditions, the objective of this paper is to investigate the effect of the climate change on urban precipitation regionally and seasonally; also to investigate if it is possible to handle the extra volume of water with green roofs.

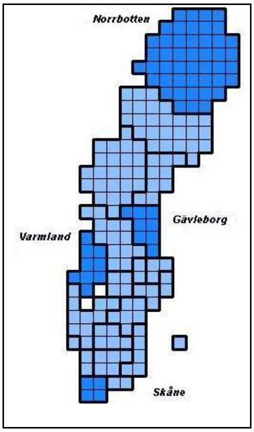

Figure 1. Four selected regions in Sweden

Methods

In this study four different regions were investigated in Sweden based on spatial variation. The first area is a southern coastal area (Skåne) adjacent to the Baltic Sea; the second area is an inland region to the west (Värmland); the third area is an inland area up north with cold climate (Norrbotten); and the *fourth* area is a coastal area along the Gulf of Bothnia to the east (Gävleborg), Figure 1. Total precipitation, maximum hourly precipitation and temperature were obtained from SMHI's open data source (Kjellström *et al.*, 2011) for these regions. The data was used to observe how the climatic parameters change over time, regionally and seasonally. An approximate analysis of the climate change impacts on the urban drainage systems was also made.

The climate data used for this study was generated by the regional atmospheric climate model (RCA3), developed by Rossby Centre, SMHI (Kjellström *et al.*, 2005). This regional model has been used to downscale the output of the global climate model, ECHAM4 (Roeckner *et al.*, 1996). The outcome from the SMHI open data source is 50×50 km spatial and monthly temporal resolution for Sweden. The data was separated into four seasons, spring as Mar/Apr/May, summer as Jun/Jul/Aug, autumn as Sep/Oct/Nov/ and winter as Dec/Jan/Feb; it should be mentioned that the seasonal classification is not based on the meteorological definition for the seasons. Each year's seasonal value is replaced with a 10-year average value, to smooth out the graphs and to present the trends in a more clear style. The first value, which is the mean value of the period between 1961 and 1971, is taken as a start or control value. The difference of each year's mean values from the control value, in percentage (centigrade for temperature), are given from 1961 to 2100. In order to analyze the trend of such changes, a line equation is calculated for each graph by the linear regression method. The value from the linear regression for the years 2050 and 2100 is used later to analyze different regions' climatic parameters.

The trends showed more precipitation in the future and therefore there will be extra volumes of water flowing into the drainage system to be handled. BMP as an alternative way of dealing with the problems was investigated. The interaction of the changes in precipitation and one of the BMP's mitigation methods, green roof, were studied for urban catchment conditions, to see to what extent it is effective in reducing the volume of the extra precipitation in an urban area.

Results and Discussion

Climate Data

The 10-year mean values from 1961 to 1971 are tabulated for Norrbotten as the control value, in Table 1. The percentage of change from the initial values is graphed for the same area in Figures 2a & b. The mean values for all regions and for different seasons are tabulated in Table 2. The mean values, calculated by the linear equations for the years 2050 and 2100, show the climatic conditions of that period.

Table 1 10-year mean as initial values

	Winter	Spring	Summer	Autumn
Temperature (C°)	*-10.7*	*-1.88*	*11.26*	*0.75*
Max Hr Precipitation(mm/s)	*3.30E-08*	*3.50E-08*	*6.10E-08*	*4.90E-08*
Total Precipitation (mm/s)	*2.20E-05*	*2.50E-05*	*3.70E-05*	*3.40E-05*

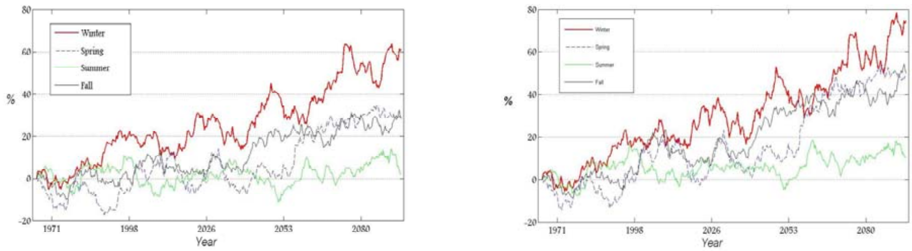

Figure 2 a) Total Precipitation Change; b) Maximum Hourly Precipitation Change; from 1961 to 2100 [%]

The seasonal variation can be seen from the results, for instance in Norrbotten the temperature values for wintertime show a positive tendency; even though the graph's peaks and dips show that the trend will change in the short term. Taking the long period analysis into consideration, the temperature will increase by 4 and 7°C until the years 2050 and 2100 respectively. The temperatures for the other seasons i.e. spring, summer and autumn, will also increase but not as much as those during winter, Table 2.

Table 2 Climatic Values Changes

Regions	*Seasons*		Winter		Spring		Summer		Autumn	
	Year		2050	2100	2050	2100	2050	2100	2050	2100
Gävleborg	*Temperature*	*(°C)*	**3.1**	**5.9**	**2.9**	**5.5**	**1.9**	**3.6**	**2.0**	**4.1**
Norrbotten			**4.0**	**7.1**	**2.2**	**4.7**	**1.4**	**2.9**	**2.4**	**4.8**
Skåne			**2.4**	**4.9**	**2.4**	**4.6**	**2.0**	**4.0**	**2.1**	**4.3**
Värmland			**2.7**	**5.3**	**2.6**	**5.0**	**1.9**	**3.7**	**2.0**	**4.1**
Gävleborg	*Max Hr Prec.*	*(%)*	**30.5**	**64.4**	**14.7**	**35.2**	**0.9**	**3.5**	**16.1**	**38.2**
Norrbotten			**31.3**	**63.1**	**16.8**	**45.5**	**6.1**	**11.0**	**20.4**	**45.8**
Skåne			**34.9**	**68.2**	**22.6**	**41.9**	**-7.6**	**-16.2**	**11.9**	**27.4**
Värmland			**32.9**	**68.0**	**26.5**	**55.5**	**-7.0**	**-9.1**	**16.1**	**36.9**
Gävleborg	*Total Prec.*	*(%)*	**15.0**	**41.0**	**-0.7**	**8.2**	**-2.5**	**-2.4**	**9.6**	**23.0**
Norrbotten			**27.1**	**54.2**	**7.2**	**27.6**	**1.9**	**4.1**	**11.6**	**28.0**
Skåne			**23.4**	**49.3**	**6.6**	**14.3**	**-13.9**	**-26.9**	**8.5**	**17.6**
Värmland			**20.5**	**46.3**	**13.9**	**32.3**	**-13.0**	**-21.0**	**6.8**	**19.5**

The total precipitations will increase for all seasons for the long period till 2100, Fig 2a. The highest increase is for winter with 54% and the lowest for summer with 4%. By 2050 summer and autumn will be the critical period with the largest volume of water (both 3.8×10^{-5} mm/s), while by 2100 autumn will alone be the critical period (4.4×10^{-5} mm/s), 13% more than during summer, 57% more than spring and 29% more than winter. Moreover, the largest increase in maximum hourly precipitation, Fig. 2b, will be during winter with 31% in 2050 and 63% by 2100. Since the mean temperature will rise and come closer to 0 C°, this might mean that some of the intense precipitation during winter can come as rain, which may result in a more rapid and larger runoff due to rain on snow events. The smallest increase will occur during summer, but since summer has the largest initial value (Table 1) it will still be the period with the second highest intense rainfall (6.8×10^{-8} mm/s in summer and 7.1×10^{-8} mm/s in autumn by 2100).

The analysis of the other region's changes shows that Skåne and Värmland will have a decrease in both total precipitation and maximum hourly precipitation during summer. It also shows that Gävleborg will have a small decrease in total precipitation for spring 2050 and for summer till 2100. For temperature, all regions will have the largest increase during winter resulting in only Norrbotten having a mean temperature below 0ºC during winter by 2100. All other seasons will have plus degrees for all regions.

For the hourly maximum precipitation all regions except Skåne have the highest value during summer for the control period (1961-1971) and for Skåne it is for the autumn. By 2050 the patterns looks the same even though the values will have increased by 1-11%. By 2100, however, the critical seasons with the highest intense rainfall will have changed to autumn for all regions except for Skåne where it is the winter. The same may be seen for total precipitation, which will also have the same critical seasons for the control period and the same change in seasons by the year 2100. Regardless of some differences in the results of the regional comparison, the general trend for all regions shows a more critical situation for urban drainage systems by the year 2100, Table 2.

Adaptation of the Urban Drainage Systems

Climate changes' most important outcome related to urban drainage is the extra volume of water entering the system. Drainage systems are mainly designed for the past and present climate conditions, while more stress will be imposed on the available systems due to increase in total precipitation, more intense rains as well as temperature increase. Therefore the systems' failure during the precipitation time will cause flooding and CSO, etc. For instance in Norrbotten, Sweden, precipitation would increase by 54% and intensive precipitation by 64%. It shows that the systems that are not designed for handling that much volume of water would not function properly. Adding snow melt to the system due to temperature increase by 7 °C makes the situation even worse.

Extra water entering the system must be handled for the future anyway. The conventional approach, renewing the traditional systems, will cause problems for future needs; since the renewing is already too slow today and changing the large number of pipes is not economically reasonable. BMP is a suitable option to mitigate the impact of climate change with the aim of having a sustainable urban area. As already mentioned there are a number of methods that can be used in urban areas. However, each region needs its own unique approach due to the fact that the functionality of the methods differs due to climatic conditions and how the overall urban plan is designed for the region. Green roof is one of BMP's methods that could be used in most urban areas, and will here be used as an example. The BMPs including green roof should be studied for each site specifically regarding their own conditions. However, as a general overview, reduction factors from published green roof studies have been used to investigate its mitigation response to different conditions. In order to apply green roof reduction to an urban catchment, 5 different levels of green roof implementation were chosen, with 5, 10, 15, 25 and 40% of the whole catchment covered by green roofs. Another factor involved in the green roof reduction calculation is the amount of water, which can be reduced by specific kinds of green roof. The studies made in north and west Europe showed an approximate volume reduction between 15 and 90% for each individual green roof for different seasons and conditions.

For extensive roofs with 50 to 150 mm thickness, the annual runoff reduction is 27-81% in the southern part of Sweden (Berndtsson, 2010), the run-off reduction is 70% for the warm season , 49% for in-between seasons and 33% for the cold season for a warm period in Germany (Mentens *et al.*, 2006). Another study (Bengtsson *et al.*, 2005) showed a 19% reduction for February, 88% for June, 34% for the period from September to February as well as 67% for March to August in southern Sweden. Even though the studies were made of a specific area, the 'Reduction' percentage used in this study, Table 3, was based on the values mentioned above and on other articles stated in the introductory section. In Table 3, the values of individual green roof reductions are converted to catchment conditions. The results are the percentages of total precipitation reduction over an urban catchment.

Table 3 Total precipitation green roof volume reduction

Reduction* (%)		15	30	50	75	90
		Cold 1	Cold 2	Mild	Warm 1	Warm 2
Green roof Area** (%)	5	**0.75**	**1.5**	**2.5**	**3.75**	**4.5**
	10	**1. 5**	**3.0**	**5.0**	**7.5**	**9.0**
	15	**2.25**	**4.5**	**7.5**	**11.25**	**13.5**
	25	**3.75**	**7.5**	**12.5**	**18.75**	**22.5**
	40	**6**	**12**	**20**	**30**	**36**

Cold 1: *very cold and wet condition*
Cold 2: *cold condition during winter and autumn;*
Mild: *mild condition during spring & autumn*
Warm1 : *warm conditions during spring and summer;* ***Warm*** 2 : *very warm summer condition*
**Total precipitation reduction from an experiment green roof unit (%); ** Implemented green roof area to the whole catchment area (%)*

Combining Tables 2 & 3 gives an idea of how an implemented green roof in an area can mitigate the volumetric effect of climate change. It is assumed that the future climatic condition of Sweden will be comparable with the approximate values from the studies in the west and north of Europe, presented in Table 3. Then the value of the individual green roof reduction for each region can be chosen from the table regarding the season and its general climatic condition in the future. The catchment volumetric precipitation reduction is calculated based on green roof area and reduction percentage.

Catchments with 15% and 40% of the whole area covered with green roofs are chosen as examples. The reductions due to green roofs are applied to the increased total precipitation by the year 2100 and then the reduction of the extra water over the catchment is calculated. To calculate the percentage of extra water reduction, the new total volume for 2100 is first multiplied by the green roof reduction in Table 3; the results are used to calculate the percentage of extra water reduction, Table 4, as a quotient between the received and the increased precipitation volume due to climate change. The seasonal comparison of extra precipitation reduction shows how effectively the green roofs function in different seasons for the different regions in the future.

According to the results, for a catchment with 15% of green roof over the whole urban area, in winter for Skåne, Gävleborg and Värmland, there would be approximately a 15 % reduction of the extra precipitation. For Norrbotten there is no reduction estimated during winter, since green roofs do not function during that period due to freezing temperature and snowing. This means that more water must be handled during melting periods later on.

Table 4 Reduction of extra precipitation in volume (values in %)

		Winter	Spring	Summer	Autumn
Gävleborg	*	15.0	99.0	-	40.0
	**	41	100	-	100
Norrbotten	*	-	20.0	100	20.0
	**	-	55	100	54
Skåne	*	13.0	60.0	-	50.0
	**	36	100	-	100
Värmland	*	14.0	30.0	-	45.0
	**	37	81	-	100

*Percentage decrease of extra water for *15% and ** 40% of area covering by green roof for the specific climatic condition in 2100*

Precipitation during summer is decreasing for all regions except for Norrbotten, which has a small increase which could not affect the system. In summer for skåne and Värmland the system will not have any problems handling the volume of water received 2100 since there will be a decrease so in that case green roof is not necessarily, while for Norrbotten and Gävleborg in the same season green roofs will be effective and can handle almost all extra pressure on the drainage systems for Norrbotten and Gävleborg. In general green roof can handle between 20 and 50% of the extra volume and these values will be up to 99% during spring for all four regions. The reduction of extra volume is different in different regions, but it seems that it is possible to handle part of the extra stress by means of green roofs' higher precipitation. If the area covered by green roof extends, for example to 40% of the whole catchment area, the reduction capacity would be increased considerably, Table 4. This shows that green roofs can be very useful and reasonable for higher urbanized regions with higher build-up density.

Conclusion

This study has addressed the climate change, its trends up to the year 2100, and the probable problems arising due to it, as well as investigating suitable methods to tackle its impacts on the drainage systems in urban areas.

The results of this study show a similar trend for the all investigated regions in Sweden towards more precipitation and higher temperature. However, the magnitude of changes is different in different regions. The highest increase will occur in Norrbotten in the northern part of Sweden, while Skåne located in the southernmost part will experience the smallest increase among all the regions. Moreover, the variation in seasonal changes is considerable. The temperature during winter in Norrbotten will increase by 7ºC, while it would be only 3 ºC warmer in summer by 2100.

Green roof as an example of the BMP methods was studied to investigate the volume reduction efficiency due to climate variation. Green roofs reduction factors and the increased values were combined where results an estimation of green roofs' extra volume reduction in different regions during different seasons. The results also showed that one specific BMP approach could not be a solution for urban areas with regional and seasonal variation. The present urban characteristics, expected future conditions and integration of them constitute a complex system, which demands detailed research considering all involved parameters as a real system. This study showed that different regions respond differently to the climate change, even though their general trend is almost the same in all regions. Besides, it also showed the importance of seasonal variation for each region; green roofs do not function in winter, while they could work efficiently in summertime in Norrbotten. As regards economic aspects, it is very important to choose the appropriate BMP method for each region. Urban areas with lower roof density cannot provide big volume reductions; however, there is probably more green area that can take care of the extra water in such urban areas. For denser urban regions where there is not enough space for green areas or expanding conventional methods, it would be very important to consider a method like green roof to use dead areas such as roofs to mitigate the extra volume of water.

Information about the variations mentioned above is an important factor for city planners and policy makers to tackle the climate change impact and guarantee a secure region for the people, and therefore more studies are needed to estimate all suitable BMP methods in order to get an overview of each region's possible alternative solution to deal with climate change impacts on the urban drainage systems.

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Paper VII

Sensitivity of urban stormwater systems to runoff from green/pervious areas in a changing climate

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Sensitivity of urban stormwater systems to runoff from green/pervious areas in a changing climate

Sensibilité des systèmes de gestion des eaux pluviales urbaines aux apports des secteurs verts et perméables, dans un contexte de changement climatique

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RÉSUMÉ

Les zones urbaines comprennent des secteurs/surfaces perméables et imperméables qui contribuent différemment au ruissellement de surface total en zone urbaine. Le ruissellement des secteurs imperméables est étudié de façon approfondie et régulière lors de l’évaluation de la capacité des systèmes d’assainissement, mais le potentiel de contribution (ou pas) des secteurs verts/perméables au ruissellement n’est pas intégralement compris. Les secteurs perméables en zone urbaine sont également considérés comme présentant un potentiel pour des mesures permettant d’adapter le système à un changement climatique à venir. Cet article étudie la contribution du secteur vert/perméable au ruissellement urbain et son impact sur les systèmes d’eaux pluviales urbains. Il se concentre sur les processus d’infiltration et d’évaporation liés aux évolutions de la pluviométrie, en utilisant une zone d’étude et une analyse de sensibilité par modèle, en modifiant successivement les paramètres physiques / du modèle à partir d’un scénario de base. Les résultats montrent que les évolutions de la capacité d’infiltration (ex. lorsque le sol est saturé ou non) ont un impact sur la zone urbaine et le système d’assainissement urbain, à la fois au niveau des volumes et des performances du système hydraulique. L’évapotranspiration (telle que décrite dans cette étude) n’est pas en elle-même un facteur significatif affectant la capacité du système d’assainissement urbain. Avec l’intérêt croissant pour la promotion et l’utilisation de secteurs verts/perméables dans l’environnement urbain, ces éléments pourraient être davantage étudiés, à la fois pour les zones construites et les secteurs naturels.

ABSTRACT

Urban areas consist of both impervious and pervious areas/surfaces which contribute in different ways to the total urban area surface runoff. The impervious area runoff has been extensively studied and routinely included when assessing the capacity of drainage systems, but the green/pervious areas’ potential to contribute (or not) to the runoff is not fully understood. The urban pervious areas are also seen as having potential for measures to adapt the system for a changing future climate. This paper reviews the green/pervious area contribution to urban runoff, and its’ impact on urban stormwater systems. It focuses on infiltration and evaporation processes related to changes in rainfall, using a study area and model sensitivity analysis successively changing model/physical parameters from a baseline scenario. The results show that changes in the infiltration capacity (e.g. when the soil is or is not saturated) will have an impact on the urban area and the urban drainage system, both in volume and on the hydraulic system performance. Evapotranspiration (as described in this study) is by itself not a significant factor affecting the urban drainage system capacity. With a growing interest in the promotion and use of green/pervious areas in the urban environment, these components should be studied further, both for constructed facilities and natural areas.

KEYWORDS

Climate change, Green/Pervious areas, Hydraulic capacity, Sensitivity analysis, Urban hydrology

1 INTRODUCTION

Urban areas comprise both impervious and pervious areas/surfaces which contribute in different ways to the total surface runoff. This runoff may have impacts on the urban area (e.g. flooding) due to limitations in the capacity of the urban drainage system. Impervious area runoff is the major contributor and has a characteristic of rapid runoff and high peak flows, whereas pervious areas have a slower runoff-pattern with a more attenuated peak. Therefore, when assessing the capacity of urban drainage systems much focus has previously been put on the impervious area runoff. When assessing impacts due to climate change on these systems, the 1D model approach (with focus on the pipe system dynamics) is the one mainly used in initial analyses. But with more extreme weather events, and the predictions that these will occur more frequently in the future (IPCC 2007), the dynamics of runoff above ground and flooding has become more important to take into account. For the use of urban hydraulic/hydrologic models, recommendations are currently a 1D/1D or 1D/2D model approach (e.g. Leandro et al. 2009). In these models the digitized terrain of the urban area is taken into account (1D/1D with a simplified flow route description, and 1D/2D with a more detailed surface terrain description). In these surface models the pervious areas have a more defined role, although the pervious/green area potential to contribute (or not) to the runoff is not always explicitly included. The urban pervious areas are, however, seen by many as offering opportunities for potential measures to improve the situation/adapt the system for the future (e.g. Digman et al. 2012).

Volume of water available for runoff, velocity of flow and magnitude of peak flow, will all increase with increasing amounts of imperviousness compared with an area with more green/pervious characteristics (e.g. Chow et al. 1988). Recent research on land-use changes, and thus the relative impervious vs pervious/green area contribution to runoff, has mostly been studied for large scale river catchments (e.g. Bronstert et al. 2002; Niehoff et al. 2002; Brath et al. 2006; Elfert and Bormann 2009; Deepak et al. 2010; Hamdi et al. 2010). Some of these studies also show the changes in runoff due to climate change (Bronstert et al. 2002; Hamdi et al. 2010). Gill et al. (2007) mapped urban morphology, to show the potential role of green area impact on urban runoff. The reduction of runoff volume and peak due to constructed infiltration facilities, BMPs/SuDS, and the process of retrofitting urban areas (e.g. Stovin et al. 2012), as well as how to include these facilities into runoff models (e.g. Soakaways, by Roldin et al. 2012a,b) is of much contemporary interest. Runoff from pervious areas (both natural and constructed facilities) is a complex process and much depends on the character of the soil and vegetation in combination with evapotranspiration potential. The infiltration processes are also related to the antecedent rainfall conditions, affecting the amount of water in the soil which may limit the infiltration rate and amount. Research in the urban hydrology field in the 1980ies revealed the importance of antecedent conditions in the urban area, affecting the runoff processes (Packman and Kidd 1980; Arnell 1982; Beaudoin et al. 1983; Marsalek and Watt 1983; Niemczynowicz 1984). Laboratory-scale simulations also showed the importance of antecedent conditions, as well as the connectivity, when comparing surfaces that were more or less impervious (Shuster et al. 2011).

Under climate change in the northern hemisphere, extreme rainfall events are likely to be more frequent. When considered in combination with the increasing use of pervious areas for adaptation urban area impact studies will need a more holistic view of the contributions from ALL urban surfaces. “Holistic” meaning here not only surface runoff patterns, but in relevant cases interactions with sea level and watercourses and also the water balance, including infiltration processes and evapotranspiration.

1.1 Objective

The objective of this paper is to study the green/pervious areas contribution to urban area runoff, and its’ impact on the urban stormwater system capacity. Focus will be on the infiltration and evaporation processes and the study use results from a small scale sensitivity analysis in the south of Sweden (Kalmar), changing one parameter at a time from a baseline scenario.

2 METHOD

2.1 Study area and model set up

The study area in Kalmar (SE of Sweden) has a population of about 3,000 and contributing catchment area of 2.23 km^2, of which 12 % is impervious (Figure 1). The urban drainage system is separate, and the stormwater model used for simulations of the area was a coupled hydraulic and surface runoff model (Mouse and MikeShe, by DHI 2008). This is a 1D/2D model set up, with a simple description of the unsaturated zone (infiltration) and evapotranspiration processes included. The saturated zone with groundwater flow dynamics was, however, not included, and there was no infiltration allowed into pipes from groundwater. The MikeShe part of the model consists of 2.23 km^2, divided in 5m*5m grid cells. The model set up in Kalmar (MikeShe) has three possible equations to use for the infiltration in the unsaturated zone: Richards equation; Gravity flow; and 2 Layer Water balance (WB) flow (DHI 2008). In the Kalmar model set up the simplest 2 layer WB flow was used.

Groundwater level was set at 1m below ground and the soil defined as mostly Moraine (with a saturated hydraulic conductivity of 5*10^{-6} m/s). Infiltration capacity was uniform (spatially) and set dry (field capacity) at the beginning of each rainfall event. Vegetation was set with a leaf area index of LAI 3, which is a mean value (LAI can vary from 0-7, depending on the growing season and vegetation type). Evapotranspiration is set at 3mm/day, which is a normal value for Kalmar in August (Eriksson 1981). This set up will be referred to as the “Baseline scenario” and is meant to represent normal conditions in the Kalmar area.

The Mouse model area consisted of 0.54 km^2 (mostly impervious areas) and the hydraulic model (1D) of 440 nodes (mostly gully pots and manholes) with three outlets (two in the north and one in the south of the system). The main outlet is in the north (about 70% of all the runoff). Time of concentration for the area at outlets is 50-60minutes, but considering flooding in all locations in the system (all nodes) most problems occur some 30min after rainfall starts. Measurements (rainfall and pipe flow) and associated calibration of the model were undertaken in 2004 according to standard procedures with iteration techniques (Håkan Strandner, DHI Water and Environment, personal communication, October 2010). The MikeShe part of the model was included as a supplement in 2008.

The two models interact at the gully pots (nodes in the Mouse model) where surface runoff and pervious area inputs (calculated in the MikeShe grid model) are passed on to the Mouse network model. Runoff from impervious surfaces (roads, buildings, paved areas) are estimated by the Mouse model (using a time-area approach) and input to the pipe network at the nodes. If water levels in the system exceed ground level (i.e. flooding) water from the Mouse model will be forced out from the nodes onto the surfaces (MikeShe) and can later re-enter the network at the same or another node.

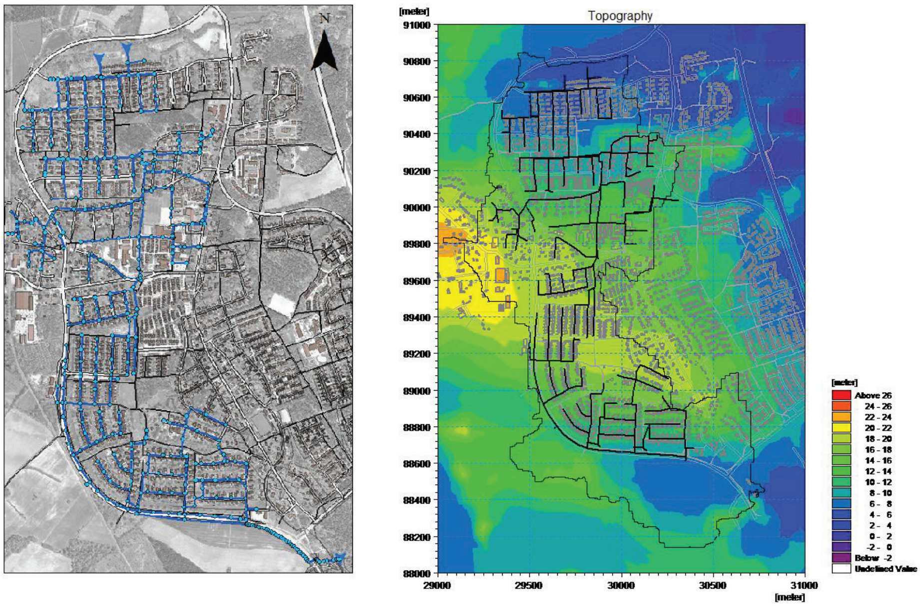

Figure 1. The Mouse hydraulic model, network of pipes and nodes (to the left). ©Lantmäteriet Gävle. Medgivande I 2001/0084. Topography and larger catchment (to the right). (DHI 2008).

2.2 Sensitivity analysis

The study was a small-scale sensitivity analysis changing one parameter at a time from the Baseline scenario in the study area in Kalmar. The Baseline scenario represents normal conditions for the area, in the summer season. Parameters included in the study are: Precipitation (one higher scenario); Evapotranspiration (one lower and one higher scenario); and the Infiltration capacity using "Soil character" as an overall description (one lower and one higher scenario). Description of the scenarios, including parameters changed in each scenario are given in Table 1.

Table 1. Scenarios in the Sensitivity analysis, and parameters changed.

Run	Scenario	P_{RP} [years]	P_{max} [mm/h]	ET [mm/d]	Soil character	K_s [m/s]	θ_s [-]	θ_{fc} [-]	θ_w [-]
1	Baseline (BL)	10	69.6	3	"moraine"	$5*10^{-6}$	0.4	0.3	0.05
2	Pres High (PH)	**10+20%**	**83.6**	3	"moraine"	$5*10^{-6}$	0.4	0.3	0.05
3	Evapo Low (EL)	10	69.6	**0**	"moraine"	$5*10^{-6}$	0.4	0.3	0.05
4	Evapo High (EH)	10	69.6	**6**	"moraine"	$5*10^{-6}$	0.4	0.3	0.05
5	Infiltr High (IH)	10	69.6	3	**"sand"**	$5*10^{-4}$	0.4	0.1	0.02
6	Infiltr Low (IL)	10	69.6	3	**"bedrock"**	$1*10^{-10}$	0.3	0.1	0.05

P_{RP} –Rainfall return period, P_{max} - Rainfall Max intensity, ET – Evapotranspiration, θ_s – water content at saturation, θ_{fc} – water content at field capacity, θ_w – water content at wilting point, K_s – Saturated hydraulic conductivity

2.2.1 Rainfall

Rainfall of a Chicago design storm (CDS, by Kiefer and Chu 1957) type with a skewness factor of 0.37 (Figure 2) was used in this study, as it is the design rainfall used mostly in Sweden. The temporal resolution was 5min, and the duration 60min. The simulations where, however, run for three extra hours after the rain ceased to include the slower processes (runoff from green/pervious areas, infiltration, evapotranspiration). In the Baseline scenario (normal conditions) rainfall of a 10 year return period was used, so as to address the current design standards of urban drainage systems (SWWA 2004). This rainfall had a maximum intensity 69.6mm/h, using rainfall statistics for Kalmar presented in national guidelines (SWWA 2004).

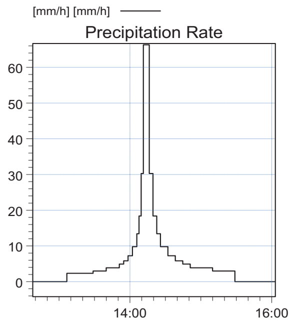

Figure 2. The CDS rainfall profile, with duration of 60min, skewness 0.37 and return period 10 years.

The rainfall parameter is included in this study to have a "climate change" reference to compare response with changes in the other parameters. Addressing changes in rainfall intensity is the most common way of taking climate change into account when performing impact assessment of urban drainage systems (e.g. Berggren et al. 2012). In current guidelines for Sweden the recommendation to take climate change into account in practice is to add a factor to design rainfall; in the Kalmar case about 20% (SWWA 2011). The new rainfall of 20% added to the original 10 year return period rainfall has a maximum intensity of 83.6 mm/h (scenario 2: PH in Table 1).

2.2.2 Evapotranspiration

Evapotranspiration and (soil) infiltration processes are interconnected, as the evapotranspiration depends on the availability of water in the soil (soil moisture) which is related to the soil characteristics and the infiltration process. The potential evapotranspiration is the maximum evapotranspiration that can occur if there is no limitation in the availability of water to evaporate. Evapotranspiration for the Baseline scenario was set at 3mm/day, which is a normal value for Kalmar in August (Eriksson 1981). For the scenarios, evapotranspiration was changed to a minimum of 0mm/day (scenario 3: EL) and to a maximum of 6mm/day (scenario 4: EH). The minimum evapotranspiration scenario represents an autumn condition with lower temperatures. For current conditions, evapotranspiration is normally at a maximum in July (4.1mm/d) based on calculations for the period 1961-1978 (Eriksson 1981), but with climate change and increasing future temperature, it is likely that this parameter can be even greater in the future.

2.2.3 Infiltration

For green and pervious areas in the urban area, the infiltration processes influence how much of the precipitation will become surface runoff (and further on enter the sewer systems), and how much of the water will infiltrate into groundwater. The infiltration capacity is dependent on the soil moisture, and the soil characteristics (ability to “keep” the water). The soil character is described as Moraine in the Baseline scenario, having a saturated hydraulic conductivity (K_s) of $5*10^{-6}$ m/s. For the two studied scenarios the saturated hydraulic conductivity was set as “Sand” with $5*10^{-4}$ m/s (scenario 5: IH, corresponding to sandy soil, where most of the water infiltrates) and to “Bedrock” with $1*10^{-10}$ m/s (scenario 6: IL, corresponding to bedrock-like characteristics with little to no infiltration normally). The soil is also described by parameters for water content at saturation (θ_s), at field capacity (θ_{fc}) and at wilting point (θ_w). Water content is the available amount of water that the soil can store at different conditions. Water content at field capacity is the maximum amount of water stored in the soil when only gravity is affecting the soil. Wilting point is the point when water is no longer available for plant uptake.

2.3 Evaluation criteria

The results from the model simulations were evaluated with the overall water balance (both in MikeShe and in Mouse), and system performance parameters: water levels in nodes; peak flow at the outlet; and pipe flow ratio.

2.3.1 Water balance

The two models were run integrated but still separated, thus the water balance results have been obtained both from the MikeShe model for the whole catchment (2.23 km^2) and details for the stormwater system from the Mouse model (connected areas 0.54 km^2). Information was obtained about the main processes of input precipitation amount, infiltration, evapotranspiration, the change in overland surface water (flooding/ponding) and the amount of runoff entering the stormwater system from Mouse impervious areas and the extra water from MikeShe to Mouse, as well as the system outlet water volumes.

2.3.2 Water level in nodes

The water levels in nodes were evaluated using both the number of flooded nodes (related to different threshold levels) and the actual water levels in every node (as suggested by Berggren et al. 2012). The numbers of nodes were counted when maximum water level exceeded each of three threshold levels (ground level, GL, and critical levels, CL, at -0.5m and -1.0m below ground). The three thresholds help to indicate the safety margin in the system. The max water levels in each node are compared in pairs between the scenarios using mean and standard deviation of differences, and a t-test at 95% significance level. The test t_0 value in this case is $t_{0.025, 439}$=1.960 (Montgomery 2001). The maximum water levels in all nodes were also presented graphically to view differences related to ground level.

2.3.3 Peak flow

The peak flow has long been a common evaluation criterion (e.g. Packman and Kidd 1980), for evaluation of the capacity of an urban drainage system, but care needs to be taken if the system is surcharged. Then the values may be representative only for the outlet or for a few points in the system. In this paper the peak flow is presented for the main outlet of the Mouse system.

2.3.4 Pipe flow ratio

As a complement to this, the pipe flow ratio (Q/Q_{full}) was also evaluated. A value of higher or equal to 1 means that the pipe was surcharged, thus evaluating this parameter also gives an indication of the system capacity. The maximum pipe flow ratio in the system and the number of pipes in the system with values equal to or exceeding 1 were determined.

3 RESULTS AND DISCUSSION

Water balance for the model simulations for both the total catchment (MikeShe- part of the model, total of 2.23 km^2) and the volumes diverted in the stormwater model and their direct connected impervious surfaces (Mouse- part of the model, total of 0.54 km^2) are shown in Table 2.

Precipitation input is different only for the scenario 2 (PH) naturally, and Infiltration is also higher. The scenario 6 (IL) shows zero infiltration as expected. The ponding of water on the surface compared with the Baseline scenario (BL) was higher for scenario 2 (PH) and much higher for scenario 6 (IL), and also the volume water from MikeShe to the Mouse stormwater system is higher or much higher for these scenarios. For the study of impacts on urban drainage systems due to increased or decreased runoff from green/pervious areas, the column “MikeShe to Mouse” in Table 2 is very important. During flooding in the stormwater system (Mouse model) water will be forced out from the nodes onto the urban surfaces (in the MikeShe model) and can then infiltrate, or later re-enter the network at the same or another node. This will affect the water balance, especially the total amount water from MikeShe to Mouse. In most scenarios this term is positive, but for the scenario 5 (IH) the high infiltration rates makes water infiltrate before re-entering the system, thus the contribution from Mike to Mouse is negative. The high ponding volume in combination with higher Mouse end volume for scenario 6 (IL), implies that the simulation was too short to take all the slow runoff processes into account. More than 3 extra hours is needed. It is, however, unlikely that these slow running volumes will affect the peak flow and maximum hydraulic impacts in the stormwater system, which is often more dependent on the faster runoff component. The time delay in runoff from green/pervious runoff is regarded as common knowledge in urban hydrology (e.g. Chow et al. 1988). A test run with longer simulation time showed the same peak flow values and maximum water levels, but with an increase of the evapotranspiration component. For all scenarios except scenario 6 (IL) the infiltration is very high for the green/pervious areas in the MikeShe model, and the runoff volume from the green/pervious areas to the stormwater system is much less than the infiltration part.

Table 2. Water Balance in the whole catchment (MikeShe), from MikeShe to Mouse, and in the stormwater system (Mouse: In/out and end volume).

	Green/pervious areas (MikeShe)					Impervious areas (Mouse)			
Run	**Precip. [m3]**	**Infiltr. [m3]**	**Evapotr. [m3]**	**Ponding [m3]**	MikeShe to Mouse **[m3]**	**Input: runoff [m3]**	**Input: infiltr [m3]**	**End [m3]**	**Output [m3]**
1: BL	37 500	34 656	1 081	764	957	4 761	17	23	5 708
2: PH	44 992	40 323	1 081	1 336	1 761	5 733	30	23	7 481
3: EL	37 500	34 885	0	853	978	4 761	17	23	5 729
4: EH	37 500	34 411	2 152	665	935	4 761	17	23	5 687
5: IH	37 500	37 082	1 074	4	-58	4 761	0	22	4 696
6: IL	37 500	2	1 082	22 041	10 949	4 761	102	347	15 378

System performance, described in terms of maximum water levels in nodes, as well as peak flow and pipe flow ratio values is shown in Table 3, as output from the Mouse-part of the coupled model. The Baseline scenario represents a normal situation in the Kalmar area, and with rainfall corresponding to 10 years return period, the system capacity was exceeded for a small number of nodes (22 of a total 440), and 115 of the pipes were surcharged in this scenario.

The climate change impact described as increased rainfall intensity (with 20% increase, scenario 2: PH) have a clear impact on the hydraulic performance of the system as expected, although for this case the low infiltration scenario (6: IL) has a greater influence. This is probably an effect of the large amount of green/pervious areas in the catchment and when the infiltration is low the volume of runoff entering the stormwater system is heavily increased (Table 2) and thus the system performance also affected. The time dependency is however also clear, the extra volume water entering the system from scenario 6 (IL) is much higher than for scenario 2 (PH) and still the hydraulic impacts in terms of number of affected nodes and surcharged pipes compared to the rainfall scenario (2: PH) is not that much higher. Peak flow at the outlet show impact on the system, but the dynamics of the whole system were better shown by the maximum water levels or the pipe flow ratio. The low infiltration scenario (6: IL) and the rainfall scenario (2: PH) make the most impact on the stormwater system, and the increased infiltration (5: IH)) makes less impact compared to the Baseline scenario. The evaporation scenarios (3: EL and 4: EH) make no hydraulic impact on the stormwater system.

Table 3. Maximum water levels in nodes, peak flow and pipe flow ratio, from the Mouse model results.

	Water levels (WL) in nodes:			Peak flow:	Pipe flow ratio:	
	Nodes	**Nodes**	**Nodes**	**Max Q_{peak}**	**Max Q/Q_{full}**	**$Q/Q_{full} \geq 1$**
Run	**WL ≥ GL**	**WL ≥ -0.5m**	**WL ≥ -1.0m**	**[m3/s]**	**[-]**	**[-]**
1: BL	22	80	147	2.04	3.00	115
2: PH	40	137	212	2.18	3.42	152
3: EL	22	80	147	2.04	3.00	116
4: EH	22	80	146	2.03	3.00	115
5: IH	15	72	127	1.90	3.02	98
6: IL	57	168	261	2.23	3.01	176

WL – Water levels relative the Ground, GL - Groundlevel

In Table 4 the maximum water levels in the nodes are shown compared with the baseline scenario (1: BL). The levels are higher for scenario 6 (IL) and for scenario 2 (PH), lower for scenario 5 (IH) and similar to the baseline (1: BL) for scenarios 3 (EL) and 4 (EH). In Figure 3, the maximum water levels in all nodes are shown graphically in boxplots relative the ground level, and as shown there is a clear difference between the baseline scenario (1: BL) compared to scenario 2 (PH) and scenario 6 (IL) which are higher. The overall capacity of the stormwater system was not significantly affected by the changes in evapotranspiration (scenarios 3, 4). The impact on the urban drainage system from a high infiltration scenario (5: IH) indicate the potential of the green/pervious areas to improve the urban drainage situation.

Table 4. Water levels in nodes, mean values, standard deviation, confidence interval and t-value for statistical evaluation. All scenarios compared with the Baseline scenario (nr1: BL).

Run vs BL(1)	**MV [m]**	**σ [m]**	**CI**		**T-value**	**P-value**
2: PH	0.354	0.329	0.322	0.385	22.53	0.000
3: EL	$8*10^{-4}$	0.008	$- 1*10^{-5}$	0.002	1.94	0.053
4: EH	- 0.002	0.010	- 0.004	- 0.001	-4.78	0.000
5: IH	- 0.127	0.141	- 0.140	- 0.114	-18.87	0.000
6: IL	0.504	0.592	0.448	0.560	17.87	0.000

MV – Mean Value period, σ – Standard deviation, CI – Confidence interval

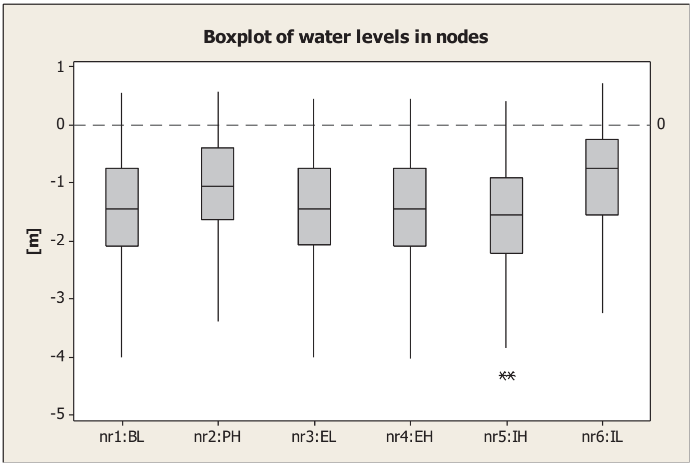

Figure 3. Maximum water levels in nodes in relation to the ground level (marked at 0m).

The impact of climate change as described as increased rainfall intensity in the precipitation scenario (2: PH) are expected to be predominant in regard to the system performance, but from this study it is also apparent that there is a risk related to the contribution of runoff from green/pervious areas to the system (when the infiltration capacity is decreased, scenario 6: IL). A decrease in infiltration capacity that occurs due to changes in the soil characteristics is unlikely and more likely due to antecedent precipitation conditions – when the soil is totally saturated and the infiltration is much reduced. Another example of situations alike are frozen ground in the autumn, and in springtime during snowmelt. A test run with higher groundwater table (at the ground level, reflecting a totally saturated soil) was also performed with similar results as with the scenario 6 (IL). In Sweden future climate scenarios predict a wetter situation, especially during winter and autumn which can cause reduced capacity for any green/pervious areas to attenuate more intense rainfall events. A combination of higher intensity rainfalls at the same time as saturated soil conditions will further worsen the situation.

The study described in this paper illustrates that natural green/pervious areas in towns and cities may also have a significant impact on the urban area as a total and also the hydraulic performance of the stormwater system. These surfaces respond to rainfall in most cases much more slowly compared with impervious areas, but are at the same time more difficult to control as they are not usually constructed facilities with a specific and defined connection to the urban piped system, unless they are specifically designed areas of green infrastructure. At times of wet antecedent conditions and heavy precipitation, these areas may contribute significantly to the total runoff volumes and, if at the same time the urban drainage system is overloaded, water from the green/pervious areas also needs to be routed around and through the urban area in the same way as runoff from impervious areas. Thus, the green/pervious area contribution needs to be given more explicit consideration as it has both a character of limiting the consequences of extreme rainfall events, but, once the attenuation capacity is exceeded, it will start instead to add to the consequences (e.g. London Borough of Croydon et al. 2011).

4 CONCLUSIONS

In this paper the runoff contribution of green/pervious areas and its' impact on the urban stormwater system capacity have been investigated using a small scale sensitivity analysis, changing parameters individually. The Infiltration and Evapotranspiration were used to represent characteristics of the green/pervious areas, and the results compared when precipitation increases more than the design standard requirements (10 year return period). This has shown that, for the Kalmar catchment:

- Infiltration processes are more important for the runoff contribution to the urban drainage system than evapotranspiration when considered separately. These processes are, however, very much related.
- The changes in infiltration capacity give large impacts on the total water balance and ponding, and may have a great impact on the system performance as well. In some cases more pronounced impacts than from changes in rainfall intensities.
- Changes in evapotranspiration cause a small relative impact on the total volume and water balance, but the difference is insignificant for the capacity of the stormwater system.
- There is a need to further study the potential of the green/pervious areas in future research, also as these areas are being used more frequently in the adaptation of urban areas to climate change.

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