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Blue-green infrastructure as a strategy for resilience

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Urban, pluvial flooding

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Blue-green infrastructure as a strategy for resilience

Johanna Maria Lykke Sørensen



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DOCTORAL DISSERTATION

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Johanna Maria Lykke Sørensen



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Det går ett träd omkring i regnet,
skyndar förbi oss i det skvalande grå.
Det har ett ärende. Det hämtar liv ur regnet
som en koltrast i en fruktträdgård.

Då regnet upphör stannar trädet.
Det skymtar rakt, stilla i klara nätter
i väntan liksom vi på ögonblicket
då snöflingorna slår ut i rymden.

*Tomas Tranströmer
Trädet och skyn
ur Den halvfärdiga himlen, 1962*

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Papers

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- I. **Sörensen, J.**, Persson, A., Sternudd, C., Aspegren, H., Nilsson, J., Nordström, J., Jönsson, K., Mottaghi, M., Becker, P., Pilesjö, P., Larsson, R., Berndtsson, R., Mobini, S., 2016. Re-thinking urban flood management – Time for a regime shift. *Water* 8, 332. <https://doi.org/10.3390/w8080332>
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- III. **Sörensen, J.**, Emilsson, T., n.d. Flood risk reduction by urban blue-green infrastructure – an evaluation using insurance data [in review for *J. Water Resour. Plan. Manag.*]
- IV. Wihlborg, M., **Sörensen, J.** and Alkan Olsson, J., n.d. Assessment of barriers and drivers for implementation of blue-green solutions in Swedish municipalities [submitted to *J. Environ. Manage.*]
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Author's contribution to appended papers

- I. The author coordinated the writing process. All co-authors contributed with texts and ideas. The author synthesised the material into an article.
- II. The author collected data, developed the method, analysed the data, discussed the results independently, and wrote the article. The co-author collected background information and helped with the discussion.
- III. The author collected data, developed the method, analysed the data and discussed the results independently together with the co-author.
- IV. The study was conducted by a master's student (first author of the paper). The author supervised the thesis, which the article is based on, together with the other co-author. All three authors further developed the theory for the study, as well as the analysis and discussion.
- V. The author took the initiative for collaboration on blue-green infrastructure and nature-based solutions. A couple of brainstorming sessions were conducted together with the co-authors. The author, together with one of the co-authors, made three interviews with in total six practitioners. The analysis, discussion and writing were made in collaboration.

Other related publications

Journal papers

- Read, K.E., Karras, M., **Sörensen, J.**, Cedergren, A., 2016. Kostnads-nyttoanalys av införandet av hållbar dagvattenhantering som riskreducerande åtgärd mot översvämning – med fokus på monetär värdering av ekosystemtjänster – Cost-benefit analysis of sustainable drainage system as flood risk reduction measure in urban areas (in Swedish). VATTEN – J. Water Manag. Res. 72, 159–168.
- **Sörensen, J.**, Johansson, A., Nordgren, M., Sternudd, C., Persson, M., 2016. Klimatanpassning mot urbana översvämningar genom transprofessionell samverkan – Adapting to flood risk in a changing climate through transprofessional cooperation (in Swedish). VATTEN – J. Water Manag. Res. 72, 177–185.

Conference papers and abstracts

- **Sörensen, J.**, Rana, A., 2013. Comparative Analysis of Flooding in Gothenburg, Sweden and Mumbai, India: A Review. Int. Conf. Flood Resilience, Exp. Asia Eur.
- **Sörensen, J.**, Bengtsson, L., 2014. Combined effects of high water level and precipitation on flooding of Gothenburg, Sweden, in: 13th IAHR/IWA International Conference on Urban Drainage. Kuching, Malaysia.
- Zhang, L., **Sörensen, J.**, Yu, H., Li, J., Persson, K.M., 2016. Quantifying Low Impact Development Measures in Water Resources Management-A Case Study, in: 2016 International Low Impact Development Conference. Beijing, China.
- **Sörensen, J.**, Aljaradin, M., Larsson, R., Persson, K.M., 2016. Recent advancements in the treatment and management of urban stormwater, in: Linnaeus ECO-TECH. Kalmar, Sweden. doi:10.15626/Eco-Tech.2016
- **Sörensen, J.**, Kalantari, Z., 2017. The link between land use and flood risk assessment in urban areas, in: EGU General Assembly. Vienna, Austria.
- Olsson, J.A., **Sörensen, J.**, Persson, A., 2017. Framework for city planning including nature-based solutions (NBS), in: EGU General Assembly. Vienna, Austria.
- **Sörensen, J.**, Emilsson, T., 2017. Insurance data as way to evaluate the performance of a sustainable urban drainage system (SUDS) in Augustenborg, Malmö, in: EGU General Assembly. Vienna, Austria.

Abstract

This thesis investigates urban, pluvial flooding and if blue-green infrastructure, for handling of stormwater in urban green spaces, can be used as a strategy for resilient flood risk management. Spatial analyses of flood claims from insurance companies and the water utility company of Malmö are used to better understand the mechanisms and characteristics of pluvial flooding and how blue-green infrastructure impacts flood risk. It was found that flooding during intense rainfall often is located closely to the main overland flow paths and the main sewers, while flooding during rainfall with longer duration seem to be more randomly distributed. Combined sewers are more affected by flooding than separate sewers. Blue-green infrastructure can reduce urban, pluvial flooding. The large-scale spatial distribution of flooding with respect to urban flow paths and drainage system are discussed in relation to the small-scale impact of surface water detention in e.g. detention basins and concave green spaces. Based on transition theory, socio-technical transition towards widespread implementation of such measures are examined through interviews with municipal and water utility officials. Legal, organisational and financial changes are suggested. A framework for management of spatial data in the strategic planning of blue-green infrastructure is also presented. The thesis consists of a summary and five appended papers, where the first paper serves as a background for the thesis.

Preface

Wet clothes, warm asphalt against my bare feet and the intense smell of rain—this is probably the strongest memory of my childhood. When a downpour suddenly appeared after a hot summer day, I ran outside to feel it, smell it, run around in it. I knew that the amusement was short, and I was soon back inside to change clothes and continue with whatever activity that had been interrupted. While this was a quick and sudden amusement, I spent hours by different small watercourses to see if I could construct a small dam, redirect the water flow a little or to just enjoy the curly waves behind a stone. When the others played games in the forest, I went to the brook.

My fascination with water started early, but I never thought it was possible to work with surface water, downpours and such. Not even as an environmental engineering student, the idea came to my mind. First when I met Jens Jørgen Linde from the sewer department in PH-Consult/Krüger (Søborg, Denmark), I started to work with hydraulics and hydrology. Quickly I got interested in pluvial flood risk assessments, operation of surface water, and climate change adaptation. When the northern parts of Copenhagen were severely flooded in August 2010, we were all taken aback by the damages. During the extreme flood event in July 2011, my husband Henrik and I suddenly found ourselves in the middle of a lake called Copenhagen,

trying to memorise what parts of Copenhagen that were on highest elevation so that we safely could drive home from the cancelled jazz concert and empty our basement from a few centimetres of water, in spite our house being situated on a hill.

When I started my research on pluvial flooding in 2012 in Lund, the Swedish discussion was focused on the 2011 event in Copenhagen. Only in 2014, when the first severe flooding hit Malmö, the discussions became really intense and at times also a bit frustrated. In Copenhagen, which was hit by the same event, the flood events had at that time become more commonplace.

From my childish fascination of the pouring rain, I have now developed a great respect for the consequences of flooding, but also a strong interest in how our cities can be built to combine flood control with an improved environment for its inhabitants. With the work I present in this thesis, I hope I can contribute to a better understanding of urban, pluvial flooding and how we can use blue-green infrastructure to reduce its impact on the city.



This work would not have been the same without the contribution from my supervisors, colleagues, collaborators, stakeholders, peer students and many others. First of all, I would like to show my appreciation to my two supervisors: Rolf Larsson and Lars Bengtsson. They have taught me about research in general and urban hydrology and flood risk management in particular. I am grateful for their contribution to my development as a researcher.

One group of researchers I am particularly thankful to is the research team of our project on Sustainable Urban Flood management (SUrF). From you I have learnt a lot, and you have widened my idea about what research is and what research can be. We have shared great moments together, trying to understand each other's perspectives, terminology and much more. Most time I have spent together with Catharina Sternudd (architecture), Per Becker (risk management), Misagh Mottaghi (urban design), Jonas Nordström (behavioural economics), Karin Jönsson (wastewater engineering), Andreas Persson (physical geography), Salar Haghighatafshar (stormwater engineering), Petter Pilesjö (physical geography), Jerry Nilsson (risk management), and of course the SUrF colleagues from my own department, Ronny Berndtsson (water resources), Rolf Larsson (hydrology), and Shifteh Mobini (flood management)—I wish to thank you all. I also wish to thank the external partners in the project. You have contributed to the project, including my research, in a very constructive way. Your part in the project have for many reasons made it more meaningful, including the practical implications of our research.

VA Syd and Länsförsäkringar Skåne have supported me with data for two of my studies and both organisations have been highly interested in the results. I am very thankful for how my collaborators in both organisations have shared their thoughts and ideas with me and how they have given me quick access to important information. From VA Syd very many persons have helped me, not the least Susanne

Steen Kronborg, Stefan Milotti, Tomas Wolf, HB Wittgren, and Henrik Aspegren. From Länsförsäkringar Skåne, Helén Nilsson has helped me with data and ideas, but also Tomas Bergkvist, Johan Litsmark, and David Lamppu have contributed in different ways.

A special thank-you to my co-authors: Shifteh Mobini (**Paper II**), Tobias Emils-son (**Paper III**), Johanna Alkan-Olsson (**Paper IV** and **Paper V**), Maria Wihlborg (**Paper IV**), Anna Persson (**Paper V**), and again the SUrF researchers (**Paper I**). With you I have had intense discussions on methodology, theory, interpretation of results and much more. Through the cooperation with you all, I have developed my research. Ironically, I am a more independent researcher after the close collaboration with you. I have also enjoyed all the time we have spent together, with many laughs and bright ideas.

I would also like to thank all students I have worked together with during these years, both those who have survived my classes and those who I have supervised during their master's thesis. It has been a pleasure to discuss various aspects of urban hydrology with you.

What would research be without a good working environment? I would like to thank my colleagues at Water Resources Engineering (TVRL) for making my everyday life in office both joyful and interesting. With inspiration from you, I get more engaged, more collaborative, and more capable. I also highly appreciate the international atmosphere of our department. A special thank you to Cintia Uvo and Rolf Larsson who strongly support my future career in the department and who help me to find my way forward.

During these years I have travelled to share ideas with researchers from universities abroad. This includes not so few people and I would like to mention some of them. Thanks to Čedo Maksimovic, Ana Mijic, Karl Smith, Kaveh Madani, Simon De Stercke, and Xi Liu who made my stay at Imperial College London stimulating and pleasant. It was interesting to see how you do research and collaborate with practitioners in the UK. I am thankful to Čedo for giving me this opportunity and also inviting me to present my research with a poster at the final seminar of the Blue Green Dream project. Other interesting universities visits I have made through the VIWAFU (Viable Water Management and Governance for Futures) courses in Riga, Copenhagen, and Palanga (Lithuania). From these courses I learnt a lot about the different water related challenges that Nordic and Baltic countries face and methods to meet those challenges. Thanks to all teachers and students of the courses. Especially I would like to thank Susanne Balslev Nielsen who ensured the high ambition and quality of the course in Copenhagen, where I also got the opportunity to share some ideas on flood management with the other students. The socio-hydrological course Water and Society in Île d'Oléron (France), organised by Isabelle Ruin, also gave many new ideas, especially about space, time and scaling in integrated research. Thanks to both Isabelle, the other teachers, and the students. More locally, I participated in the ClimBEco research school, coordinated from Lund. This summer

school gave me an opportunity to see how researchers in natural sciences work and the mentoring programme gave me an opportunity to think more closely about my own goals and progress. I am certainly thankful to my mentor, Guy Schurgers, for spending time with me, sharing thoughts and ideas from his own career within academia. Our conversations have meant a lot to me.

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As mentioned before, my interest in urban hydrology, pluvial flooding, and climate adaptation was first awakened during my work in PH-Consult/Krüger in discussions with Jens Jørgen Linde and other good colleagues. During those years, a group of ‘stormwater nerds’ from Krüger and other companies regularly met to discuss and enjoy a good meal together. I still meet with Sara Lerer, Roland Löwe, and Luca Vezzaro every now and then and I am grateful for their friendship and their support in my research.

Besides the friends I have met during the work with this thesis, I am thankful to all friends outside academia. It is definitely good sometimes to let the mind focus on something else than water, water, water. I love to develop my interest in hiking, gardening, knitting, juggling, and music together with you. Thanks to all of you! And finally, and most of all, I am grateful for the wonderful family I have. Thanks to all relatives, including all grandparents that now have passed away. You mean and meant a lot to me. And thanks to my husband Henrik, my son Karl, my mother Birgitta, my father Irwin, and my brother Joakim for always being there—thank you for your love, care and company.

Introduction

Urban flooding typically originates from rivers (riverine or fluvial flooding), sea (coastal flooding) or rainfall (pluvial flooding) and is problematic in many cities. Severe flooding has hit highly developed cities like Prague, Dresden, and several other cities (2002, riverine flooding), Bern and several other cities (2005, riverine), New Orleans (2005, hurricane), Copenhagen (2010, 2011, and 2014, pluvial), New York (2012, hurricane), and Ellicott City in Maryland (2018, pluvial), as well as areas like Queensland (2010, flash flood & riverine), south-western England (2013–2014, coastal, pluvial, riverine & groundwater), the French Riviera (2015, flash flood), and Hiroshima (2018, flash flood). The societal consequences are severe and flooding in urban areas is costly, especially in central areas. In Nordic countries recent floods have caused severe losses. In 2002, several villages on the island Orust outside Gothenburg, Sweden were isolated because of pluvial flooding from 270 mm rainfall, and the damages covered by insurance companies were estimated to MSEK 123 (~ MEUR 15) (MSB 2013). The insurance costs after the pluvial flood in Copenhagen, Denmark in 2011 were estimated to more than MUSD 800 (~ MEUR 580) (Swiss Re 2011). The direct economic losses of the extreme rainfall event in Malmö, Sweden in 2014 were estimated to MSEK 600 (~ MEUR 60) (City of Malmö 2016). There are few flood events reported to the international disasters

database (EM-DAT) from Nordic countries between 1970 and 2005, compared to countries like Italy, Spain, France and Germany (Barredo 2007). Only one major event was reported from Sweden, a spring flood in Bergslagen 1977. River floods, flash floods, and storm surge cause most damage and casualties in Europe (Barredo 2007).

The global statistics, as registered in EM-DAT, shows that floods cause enormous damage. It was the second largest natural cause of economic loss (after storms) and accounted for 47% of all weather-related disasters between 1995 and 2015 (CRED & UNISDR 2015). During 1980–2010, floods affected almost 90 million people worldwide and 15% of the world's population will live in flood-prone areas by 2050, not taking climate change into account, meaning they are threatened by flooding (Ligtvoet et al. 2014). Floods have a large impact on human well-being and economy (CRED & UNISDR 2015). Besides loss of human life and human health effects (Hajat et al. 2005), flooding leads to ecosystem degradation and damage to economic, historical and cultural values, as well as decrease of socio-economic welfare (Kabat & Schaik 2002). Most of the death tolls from natural disasters are reported from low-income countries, while the economic losses are higher in high-income countries, reflecting the accumulation of economic wealth there (CRED & UNISDR 2015). The figures on flooding, as collected by EM-DAT, have varied dramatically between decades during the last hundred years (Roser & Ritchie 2018). The global statistics on disasters do not separate different types of flooding, but most probably riverine and coastal floods are the most deadly, as they often affect large areas.

The effects associated with global warming, such as sea level rise and associated backwater effects in rivers, as well as more intensive precipitation, may increase the frequency and the extent of flooding on a worldwide scale. Global average precipitation is projected to increase, but both increase and decrease are expected regionally. According to Milly et al. (2002), the worldwide frequency of riverine floods has already increased during the twentieth century. Several reasons for the increase have been suggested, such as changes in flow regime (Poff et al. 1997), land use changes (Leopold 1968, Poff et al. 1997), and climate change (Milly et al. 2002). Increased population together with economic growth leads to more damage (Ligtvoet et al. 2014). In Europe, a small increase in flood frequency between 1970 and 2005 is reported for major floods (direct damage larger than 0.005% of the EU GDP and/or more than 70 casualties), while the number of total reported floods (including smaller events) shows a greater increase (Barredo 2007). The total losses in Europe are estimated to approximately EUR 4.9 billion annually (2000–2012) and expected to increase to approximately EUR 23.5 billion by 2050 (Jongman et al. 2014). The projection is however highly uncertain (ibid.).

Pluvial flooding is defined as unintended inundation of land that causes damage because of heavy rain. When rainfall volumes exceed drainage capacity of natural and constructed systems, low-lying areas are inundated with water. Rainfall is, by definition, the main driver of pluvial flooding. In urban areas, pluvial flooding is

controlled (or not controlled) by conduit and detention of stormwater in major and minor systems. Land use and drainage are in urban areas highly modified, compared to natural land. Pluvial flooding might increase in the future because of extensive urban and suburban growth (UN 2015a, Ligetvoet et al. 2014), insufficient sewer systems (Swan 2010) as well as climate change (Semadeni-Davies et al. 2008a,b). In Scandinavia, both annual precipitation and extreme rainfall events during summer is projected to increase (SMHI 2015, SMHI 2017a). Flooding from downpours might thus increase, while spring floods might decrease due to shorter snow season. In this work, focus is on pluvial flooding because of its close connection to stormwater management and the urban landscape.

The situation in cities like Malmö, where some of the studies in this work have been conducted, is different from the most vulnerable megacities, like Dhaka, Kolkata, Shanghai, Mumbai, Jakarta, Bangkok and Hoh Chi Minh City (Ligetvoet et al. 2014). While the megacities mentioned are threatened by both riverine and coastal flooding, Malmö has no major river and is, in comparison, well protected from storm surge. It is therefore natural to focus on pluvial flooding, which has led to large damages in Malmö and other cities in Nordic countries and elsewhere (Houston et al. 2011, MSB 2013). Despite the difference in urban density compared to the megacities, there have been several casualties reported during urban floods in Europe (Barredo 2007), adding on to the importance to manage urban flooding also in developed countries. Pluvial flooding has in common with riverine flooding the climatological (Glaser et al. 2010) and hydrological (Berghuijs et al. 2016) drivers as well as the effect of human activities (Zhang et al. 2014). However, pluvial flooding acts on a different scale than riverine flooding. While riverine flooding is caused by excessive rainfall or snow melt over an extended period, pluvial flooding is triggered by high-intense rainfall that is typically shorter in duration. While riverine flooding results in severe inundation close to the river, pluvial flooding can affect any low-lying place. And while riverine flooding is affected by land use changes on regional scale, such as extensive draining of wetlands and intensified agriculture, pluvial flooding is affected by small-scale land use changes in urban areas, such as increased use of impermeable pavements. These differences necessitate research to investigate mechanisms and characteristics also for pluvial flooding, despite extensive research on causality of riverine flooding. Also, the measures to control pluvial flood differs from those to control riverine and coastal flooding.

Adaptation of systems for urban drainage

The traditional engineering approach to manage urban drainage is by combined or separated sewers. In urban catchments, drainage systems may include different

types of storage and detention facilities to avoid flooding from heavy rainfall. However, during recent decades, alternative ways to manage floods have evolved since traditional methods often harm the riverine ecosystems by pollution and erosion and increase the flood risk in the downstream extent of a catchment (Liao 2012).

Densification has become a dominating urban planning strategy, as many cities strive to reduce their negative, environmental impact (Ståhle 2008). With a high number of impermeable surfaces, urban land is more vulnerable to flooding than the surrounding environment. The current, centralised sewers put a pressure on urban areas and their surroundings, both by increased flood risk and by high pollution loads related to combined sewer overflow (CSO) as well as stormwater runoff from polluted surfaces. To mitigate negative effects of densification, such as loss of ecosystem functions and services, alternative stormwater management solutions have been used since the 1970s (Niemiczynowicz 1999, Cettner et al. 2012). During later years, green infrastructure planning with the social perspective in mind has been called for. Schiffman (2017) claims that the perspective must be shifted from hydrologically driven to an integrated, socio-hydrological approach, where values such as increased property value, greenspace aesthetics, heat island amelioration, carbon sequestration, and habitat for biodiversity are included. In this thesis, the term blue-green infrastructure is used to clarify the need of integrated solutions with a holistic view of the water cycle as well as an ecosystem perspective. As a consequence of urban densification, the need for solid strategies to preserve, build, develop and ideally simultaneously increase the quantity (area) and quality of green and blue spaces (vegetation and surface water) in urban areas in a multifunctional manner increases (Hansen & Pauleit 2014). When developing these strategies and concretely implementing new blue-green infrastructure, it is important to ensure that these areas are able to respond the broad array of challenges caused by urbanisation brought to the fore by goal 11 of the UN's 17 Sustainable Development Goals, expressing the aim to "make cities (...) inclusive, safe, resilient and sustainable" which includes to provide access to green and public spaces for all strata of society and to reduce the number of people affected by water-related disasters (UN 2015b).

Another problem with current stormwater management is related to aging sewers and/or lack of proper maintenance. About half of the sewers in Sweden were constructed during 1960s and 1970s and in total two thirds were constructed before 1980 (Malm et al. 2011). While most concrete pipes last for 60–110 years if they were constructed before 1970 and 110–140 years if they were constructed after 1970, some only last for 20–40 years (*ibid.*). Many pipes have begun to show signs of deterioration and it expensive to meet the need for new investments with new pipes and enlarged capacity (*ibid.*). To avoid replacement of existing pipe network, some areas can be disconnected from the sewers to reduce load from them, and mains and distribution pipes can be rehabilitated with no-dig methods like pipe lining. These methods are often less expensive than traditional open cut replacement methods.

The combination of climate change adaptation, densification, pollution, the call for more green spaces, and a need to restore aging sewers, leads to strong interest in retrofitting of urban areas with blue-green infrastructure.

Blue-green infrastructure as a sustainable urban drainage solution

Blue-green infrastructure can contribute to the urban environment with multiple benefits: water supply, flood mitigation, terrestrial biodiversity, urban cooling, resilience to climate change effects, urban agriculture, and human well-being (Turner 1995, Walsh et al. 2016). Preferably, blue-green infrastructure should be well-integrated in the urban landscape to achieve multiple benefits and thereby decrease the amount of land needed for every single infrastructure element. Drawbacks, like risk of unwanted insects, and issues related to water safety and accessibility for the people with physical disabilities, must be handled in a proper way. In this work, the main focus is on how blue-green infrastructure can contribute to improve the urban water cycle, i.e. to reduce total runoff and decrease peaks, by detention, infiltration, and evapotranspiration of urban stormwater to reduce pluvial flood risk (Stewart & Hytiris 2008, Qin et al. 2013, Liu et al. 2014, Zahmatkesh et al. 2014). These hydrological processes act differently for different time scales, i.e. precipitation durations. Blue-green infrastructure is also used to ensure controlled flooding in concave green areas or detention basins (Liu et al. 2014). As this work concerns urban, pluvial flooding, the most extreme rainfall events are considered, typically with short duration, e.g. a few hours.

Incorporation of blue-green infrastructure and resilience into decision-making and ways to handle integrative and multi-criteria aspects in the legal and organisational system are still to a great extent not done. The current regime for stormwater management, through piped drainage, is dominating (Ashley et al. 2011, Cettner et al. 2013). An urban planning approach integrating technical, social, environmental, legal, and institutional aspects of stormwater management is crucial (Zhou 2014). Introducing such an approach is faced with barriers that are largely socio-institutional rather than technical (Brown & Farrelly 2009a). In this work such barriers, as well as drivers, for wide-spread implementation of blue-green infrastructure, as well as data management strategies to help the implementation, are investigated.

Objectives

This study has its base in a hydrological perspective on urban, pluvial flooding. From this perspective, it reaches further to study socio-technological transition in

the context of changed urban environment and climate change. Strategies for retrofitting of urban areas and urban drainage systems in a decentralised manner with the use of blue-green infrastructure are examined. The overall purpose is to better understand if urban, pluvial flooding could be mitigated with blue-green infrastructure as a strategy for resilient flood risk management and how wide-spread implementation of such measures could be done.

The detailed objectives are:

- to discuss urban flood risk management from a multi-disciplinary perspective (**Paper I**),
- to develop a framework for urban flood risk management (**Paper I**),
- to analyse the spatial distribution of flooding and its spatial relation to drainage system, flow paths, rainfall patterns, and sea level (**Paper II**),
- to understand the characteristics and mechanisms that govern the effect of flooding (**Paper II**),
- to understand the role of blue-green infrastructure for risk reduction (**Paper III**),
- to understand the barriers and drivers for a socio-technological transition from pipe-bound drainage to blue-green structures for stormwater management (**Paper IV**), and
- to develop a framework for data collection and management for spatial planning of blue-green infrastructure in urban areas (**Paper V**).

Structure of this thesis

After the introduction, a theoretical background to the studies is given, including some of the concepts presented in **Paper I**. The work is based on five scientific papers (appended). **Paper I** presents a framework for flood risk management. Effects of extreme precipitation in urban areas are then studied in full city scale (**Paper II**) and in a neighbourhood retrofitted with blue-green infrastructure (**Paper III**). In **Paper IV**, barriers and drivers for implementation of blue-green infrastructure are assessed and in **Paper V** a framework for data management with geographic information system (GIS) in the planning of blue-green infrastructure is presented. The studies in **Paper II, III, IV**, and **V** are described in the study area, methods, and results chapters, while **Paper I** serves as a theoretical framework presented in the section about flood risk management in the theoretical background. The results from the studies are analysed and discussed in relation to findings from other studies in the discussion chapter, where some implications of the work and a few deliberate suggestions for the future also are discussed. The thesis ends with a short chapter presenting the most important findings.

Theoretical background

Extreme precipitation

An extreme event is only extreme in relation to the normal. Extreme precipitation cannot be defined by its impact on the society, i.e. how severe hazard it leads to, or what the systems normally are designed for, i.e. the design standard. Both these perspectives would lead to a definition where an event would be considered less extreme as the society gets better prepared, or as the standards are changed. It might be more correct to define the extremeness in relation to how common the precipitation in itself is; the lower frequency the more extreme. In urban hydrology, a 100-year event is often considered extreme (Hoang & Fenner 2016, Madsen et al. 2014). However, even this definition has its limitations. After an extreme event, the statistics are often updated, despite the statistical distribution and the physical reasons behind it has not changed. While stationarity often is assumed for statistical analyses of extreme precipitation, despite fluctuations in climatic forcing, the assumption must be re-evaluated with climate change and the pillars of this definition shake. As more extreme events appear, what was before considered extreme are not any longer perceived so. What used to be a 100-year event will happen more frequently, leading to new thresholds for extremeness. Still, this definition is probably the most useful,

but it must be set in relation to the local context. What is a normal rainfall in tropical monsoon climate is considered extreme in temperate or arid climate. As this work focuses on flooding in southern Sweden, extreme precipitation relates to the climate here, which is *warm temperate climate, fully humid with warm summer* (Cfb), also called *oceanic climate*, according to the Köppen-Geiger climate classification (Kottek et al. 2006).

For extreme precipitation to fall, either sufficient moisture must be available for a convective thunderstorm to be developed by solar heating, or moisture must be advected into the region and released by an uplift mechanism (Gustafsson et al. 2010). Extreme daily summer rainfall in Sweden from advection is governed by atmospheric circulation characterised by air-masses that collect moisture over the European continent and the Baltic Sea (Gustafsson et al. 2010). While convectonal rainfalls are typical for the tropics, they are also common at higher latitudes, particularly in the summer. As the ground gets heated, air bubbles rise 10–12 km and form cumulonimbus clouds from which intense rainfall is released when they cool to condensation temperature (Shaw 1988). The rain cells are often too small to be captured by point measurements (Wern 2012). The most severe downpours in Sweden typically hit Scania, eastern Götaland, Svealand and the southern coast of Norrland (Wern 2012). Most events of extreme precipitation in Sweden are reported in July and August and a weak correlation between high summer temperatures and number of days with extreme daily rainfall was found in a study by Wern (2012). There is no correlation between high annual precipitation and extreme daily rainfall in southern Sweden (Wern 2012, Bengtsson & Rana 2014).

In Sweden, about 70% (range 52–81%, but most often within 70–80%) of the extreme events occurred during cyclonic weather type during 1961–2000, compared to only 45% for the non-extreme events, where extreme events are defined as more than 40 mm daily rainfall and non-extreme events as 1–40 mm daily rainfall (Hellström 2005). However, the southernmost region of Sweden, including Scania, differs from the other regions. Here the difference in weather type is less distinct (ibid.). Extreme events were in the southernmost region to 52% related to cyclonic weather (non-extreme 27%), to 39% related to anticyclonic weather (non-extreme 23%) and to 10% related to directional weather types (non-extreme 50%) (ibid.).

The Swedish Meteorological and Hydrological Institute (SMHI) mainly measures daily precipitation. Therefore, most Swedish studies are based on daily precipitation, but early studies with data from Hellman rain gauges and more recent studies with tipping bucket data do also exist (Dahlström 2006). Only 120 of 750 SMHI stations use automatic registration, where typically registration is done every 15 minutes since the 1990s. For the rest, manual registration is done once a day (SMHI 2017b). As the measurements are registered as 24 hours totals recorded at 07:00 local time, it is difficult to compare studies done with these data with statistics from other stations (Hernebring & Salomonsson 2009). High resolution data from e.g.

tipping buckets are only registered by municipalities, utility companies and on private initiative. In Sweden, extreme precipitation is often defined as 40 mm of daily precipitation (Hellström 2005, Gustafsson et al. 2010). The return period for such an event is between 2 and 5 years (Wern 2012). The 10-years event is in the range 45–55 mm/day and the 100-year event in the range 60–100 mm/day in southern Sweden (Bengtsson & Rana 2014). SMHI defines downpour (in Swedish: *skyfall*) as minimum 50 mm in an hour or minimum 1 mm in a minute (Wern 2012), which in Malmö corresponds to a return period between 50 and 100 years (Hernebring et al. 2015).

Many studies from Northern Europe have found an increased number of extreme rainfall events during the last 50–100 years (Madsen et al. 2014). However, in Sweden no significant trend has been found (Bengtsson & Rana 2014). The 1970s was a very dry period in Sweden, especially in southern Sweden (Lindström & Bergström 2004). During 1807–2002, the years of 1951 and 1924 stand out as most notable (riverine) flood years, but also during the 1990s several big floods were noted (Lindström and Bergström 2004). Future precipitation patterns cannot be predicted from analysis of historic data only. Instead, climate models must be used (Wern 2012) in combination with historic data. Increase in short-duration extreme intensities of 5–10% are projected from such models in Stockholm, Sweden, by 2011–2040 and 10–20% by 2071–2100 (Olsson et al. 2012) and in Kalmar, Sweden, the highest 30-min summer intensities are expected to increase by 20–30% and the highest 30-min autumn intensities by 50–60% until 2100 (Olsson et al. 2009). In Denmark extreme precipitation for durations between 1 and 24 hours are projected to increase by 10–50% within the next 100 years (Arnbjerg-Nielsen 2012). The projected climate in southern Sweden is on the border between Cfa and Cfb as classified by Köppen-Geiger (projected with Tyndall temperature and precipitation data for the period 2076–2100, A1FI emission scenario) (Rubel & Kottek 2010). The difference between the two climate classes is that summer is *hot* instead of *warm* in Cfa, compared to the current climate class in the region, Cfb.

Research on extreme events are somewhat complicated, mostly as it is difficult to make measurements under extreme conditions, for several reasons: 1) as water flows in unexpected directions during extreme rainfall, measurements might not be taken at the places where they are most useful. 2) Often equipment is destroyed during extreme events. After a severe flood event in 2011 in Copenhagen, it took more than a month to repair one of the main pumping stations and to get real time data from it again. 3) The events are obviously rare, meaning there are few data points to make statistics from, leading to big uncertainties.

Pluvial flooding

Floods are usually categorised by the governing mechanism. The most common flood types are coastal (from storm surge, sometimes in combination with high tide), riverine or fluvial (from river overflow), and pluvial (rain induced) flooding. Flooding can also appear as groundwater flooding or be caused by dam breaks, damage to water supply or drainage system. Riverine floods in mountainous landscape is often called flash floods, because of their sudden appearance. In this work, pluvial flooding, which is the main focus, includes surface water flooding and flooding by exceedance water from the drainage systems. Extreme precipitation has already been discussed in the previous chapter. The theoretical background for other drivers for urban, pluvial flooding are presented below. The mechanisms and characteristics of pluvial flooding in Malmö is further investigated in **Paper II** and **Paper III**.

The hydrology in urban areas differs from the surrounding landscape (Lull and Sopper 1969). While infiltration and evapotranspiration are significantly reduced with urbanisation, both overall discharge and peak flow increase. With urbanisation, time of concentration usually decreases. The rapid flow, caused by shorter lag time to peak flow, leads to increased flood risk (Anderson 1970). Runoff mainly from impervious (Bigwood & Thomas 1955, Boyd et al. 1993), but also from pervious surfaces (Berggren et al. 2013) is the governing hydrological process for urban flooding. Runoff from impervious surfaces equals the precipitation volume, with a small initial loss and some delay. While the runoff process from impervious surfaces is more or less the same for all storms, runoff from pervious surfaces are related to the rain depth. For storms larger than 50 mm, soil saturation before the storm is important (Boyd et al. 1993) and precipitation prior to extreme rainfall events have a significant impact on flooding (Torgersen et al. 2015). During extreme rainfall, the green/pervious areas contribute to runoff (Berggren et al. 2013).

The hydrological behaviour of urban surfaces is complex, depending on age, slope, maintenance, etc. (Redfern et al. 2016). The runoff is different for different soils and therefore the effect of urbanisation differs between areas with for instance clayey soils and sandy soils (Sjöman & Gill 2014, Redfern et al. 2016). During winter time, frozen ground increases the runoff. High groundwater level also increases the runoff as less water can infiltrate. Redfern et al. (2016) reviewed a number of field experiments on impermeable surfaces and green spaces. They found that roads often infiltrate more than assumed in hydrological modelling of urban surface, up to 50–60% of rainfall when deteriorated, while only 2–3% when they are new. Urbanisation impacts the urban soils as top soils often are removed and interchanged with new soil material, vegetation is lost, and soils compacted. The soil is also affected by changed local climate and other indirect impacts. Therefore, urban green spaces can generate up to 60–70% runoff when newly established and 5–30% after some years. The natural hydrological soil characteristics can be restored by tree planting and root development (ibid.).

In general, the peak discharge from a catchment increases with shorter time of concentration, meaning that it is important to delay the runoff to reduce flood risk (Villarreal et al. 2004, Fletcher et al. 2013, Locatelli et al. 2015, Rizzo et al. 2018). With centralised sewers, large amount of water is led from an upstream area to a downstream area. This might lead to flooding in downstream areas, due to the fast conduit, but may also cause problems along main pipelines as the systems seldom are designed for more than 10-year events. The temporal pattern of a rainfall also influences peak flood depth, where flood depth is greater for storms with high intensity rainfall after some lower intensity rainfall, compared to the opposite (Hettiarachchi et al. 2018), probably because of soil saturation and fill up of detention ponds before the most intense rain falls.

The response of the drainage system to rain events in the urban environment is characterized by two main components (Bengtsson et al. 1993). The first is the surface runoff on natural slopes, i.e. the major system. The second component consists of the artificial drainage system, i.e. the minor system. In most cities, the artificial drainage system is either controlled by a combined sewer network, which collects both stormwater and wastewater and leads it to the treatment plant, or by separate surface water sewers. While the major system often is neglected in the urban planning, leading to construction in low-lying, high risk areas, the minor system is typically designed according to a certain, locally or nationally set design standard. During most rainfall events, piped drainage systems safely conduit stormwater from urban areas to a wastewater treatment plant or recipient. However, drainage systems designed to cope with the most extreme storms would be too expensive to build and operate (Fratini et al. 2012). In establishing tolerable flood frequencies, the safety of the residents and the protection of their valuables must be in balance with the technical and economic restrictions.

In urban areas, flooding may be associated with failing sewer systems. Despite proper design, the urban drainage system might flood even during minor rainfall events due to problems like pump failure (UK Environment Agency 2007), misconnections (Ellis & Butler 2015), gully pot blockage (ten Veldhuis 2010), and lack of maintenance (Arthur et al. 2009).

Pluvial flooding of urban areas can be expected. Therefore, conduit systems must be dimensioned accordingly, including blue-green infrastructure. The flood risk must be managed in a proper way with a combination of stormwater control, landscaping and social preparation.

Historical development of urban drainage systems

Sanitation has been a great step forward for mankind and can be regarded as the most important medical achievement (Ferriman 2007). Without proper drainage, cities are smelly, unpleasant and even dangerous to live in, and many places would not be possible to develop without drainage.

Urban drainage in Sweden has gone through a long development, from the first piped solutions, to introduction of wastewater treatment and later separation of sanitary sewers and stormwater pipes (Cettner et al. 2012). Similar development is seen worldwide (Brown et al. 2009, de Feo et al. 2014), where the Swedish urban drainage to a great extent has followed engineering standards in the UK and Germany (Bjur 1988, Cettner et al. 2012). Before pipes were constructed for drainage in urban areas, sewerage was deposited through a hole in the wall, the door, or a window and flushed away with rain. Faeces were stored in the backyard, collected, and used as fertiliser on agricultural land (Figure 1, A). Cities were smelly, and hygiene was bad. After several outbreaks of diseases like cholera, action was called for and pipes were constructed to drain the streets from around the 1860s and in the 1880s twelve Swedish cities had piped drainage systems (SEPA 2013). In the beginning, water closets were not allowed, as collection of faeces was an important source of fertilisers, but

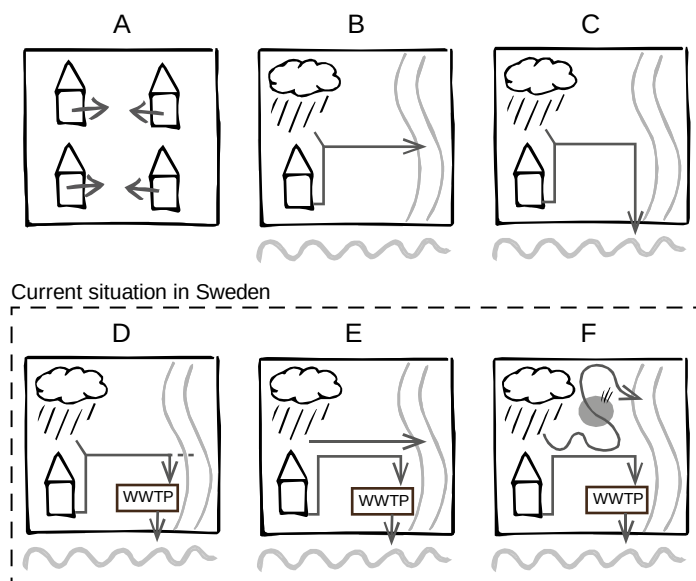


Figure 1. Stages of development of urban drainage systems in Sweden. A) sewerage deposited to street, B) drainage of streets through piped sewers, C) pipe system connected with interceptor sewers, D) wastewater treatment plants to treat sewerage, E) separate foul and surface water sewers, F) detention and treatment of stormwater in vegetated swales, channels and ponds. The dashed line marks the currently used systems in Sweden.

during 1920s and 1930s outhouses were replaced with water closets in many homes (Hatje 2018). A few wealthy people started to illegally install water closets even earlier (Lindegård 2001). At this time, sewers were often seen as a way to promote civic pride (Cettner et al. 2012). Through construction of pipelines for drainage, cities could be promoted as well developed, modern, and with perspectives of the future (ibid.). In the beginning, the outlets were typically located in a nearby canal, stream or lake (Figure 1, B). Later, outlets close to the city were shut down and interceptor sewers were constructed, often incorporating stretches of polluted, urban watercourses, which led the sewage further away to bigger rivers, lakes, or to the coast (Figure 1, C). Still, sewage was discharged without treatment. In 1950s and 60s, pollution of streams and waterborne diseases led to public health interventions for treatment of sewage in wastewater treatment plants (Figure 1, D). Already in the 1940s, some engineers argued for separation of sanitary sewage and stormwater, as the wide range between minimum and maximum flows made self-cleansing more difficult in combined sewers (Camp 1946), while other engineers argued against (Palmer 1950). Construction of separated sewers, with a foul sewer to carry contaminated wastewater and a surface water sewer to carry stormwater to receiving waters, did not become common practice in Sweden up until the mid-1950s (SWWA 2000, Malm et al. 2011) (Figure 1, E). In the 1970s, ideas of environmentally friendly drainage of stormwater started to develop (Niemczynowicz 1999, Cettner et al. 2012, Fletcher et al. 2015) (Figure 1, F). The main focus in the 1970s was detention, retention and recharge in ponds and detention basins (Niemczynowicz 1999, Stahre 2006). During the 1980s and 1990s, focus shifted slightly towards stormwater pollution and more efforts were made to protect the natural water cycle by local source control, flow attenuation and treatment (Niemczynowicz 1999). Urban drainage continues to develop, and new concepts and views are continuously presented (Brown et al. 2009, Ahern 2011 & 2013, Walsh et al. 2016).

The current situation in Sweden is a mixed use of drainage systems, where separate sewers dominates (Figure 1, E), while combined sewers still are used in 20–25% of urban areas (Figure 1, D) (SWWA 2000). Only a small fraction of urban stormwater drainage is done in decentralised manner (Figure 1, F). All sanitary and combined sewers are connected to wastewater treatment plants, while separate stormwater only is treated to a low degree in Sweden.

Problems related to current stormwater practices

As urban areas are developed, land becomes less pervious (Lull & Sopper 1969), leading to increased runoff (Leopold 1968). Traditionally, urban runoff has been collected in drains and conveyed through concrete channels and pipes to receiving waters or wastewater treatment plants. The piped drainage has a central role for the clean and modern cities (Cettner et al. 2012), but the fast and efficient conduit of

stormwater from urban spaces also leads to several problems. Urban, pluvial flooding has already been discussed earlier in this chapter. Below, other problems related to our current drainage system are presented.

For receiving waters, erosive flow frequencies increase with urbanisation, at the same time as base flow in urban streams are reduced because of the low infiltration rates. Urbanisation leads to changes in the aquatic ecosystems by e.g. reduction of fish population, and decreased diversity of algae and macrophytes (McGrane 2016). Pollution from heavy metals, PAHs, PCBs, pesticides, and pharmaceuticals as well as macronutrients (N/P/K) increases, often discharged with urban runoff through large storm sewers (Whippel et al. 1978, Characklis and Wiesner 1997, McGrane 2016). Compared to farmland, urban areas pollute with more heavy metals, but with less nutrients (Berndtsson & Bengtsson 2006). The loads of suspended solids (SS), to which heavy metals and other pollutants often are attached, are higher in stormwater runoff than in raw sanitary sewage, while both volatile suspended solids (VSS), chemical oxygen demand (COD), biological oxygen demand (BOD), phosphate, and total nitrogen are lower (Weibel et al. 1964). Pollution from combined sewer overflows (CSO) are problematic in many places. In Sweden, much has been done the last 25 years to reduce CSO loads. The three biggest cities (i.e. Stockholm, Gothenburg and Malmö), have reduced their loads with 50% (Wennberg et al. 2017). Stockholm has lower CSO loads compared to the other two, mainly because of the vulnerable recipient Lake Mälaren. Many mid-size cities, like Halmstad and Helsingborg, have managed to reduce their loads with 90% since 1992, often as an effect of their efforts to reduce problems with reoccurring basement flooding (ibid.).

Misconnections, where wastewater is discharged into surface water sewers, are common (Ellis & Butler 2015). In some parts of London, as many as one in three households lead their wastewater untreated to rivers and streams because of such domestic misconnections (Thames Water 2016). The opposite kind of misconnections, where stormwater runoff is discharged into foul sewers, leads to unintentionally high pressure on wastewater treatment plants and increased risk of flooding. The misconnections are difficult to find and correct, as the sewers are hidden underground and sometimes not sufficiently documented.

Some sewers were constructed in central urban areas more than hundred years ago. These, and also much younger pipes, that even might have a lower standard, call for refurbishment due to degradation. In many places, the maximum capacity of existing sewers is reached, making it difficult to densify urban areas further.

Small creeks are often removed as a part of urbanisation, like for instance in Shanghai (Wu et al. 2012), London (Hattab et al. 2017) and Lund, Sweden (Deak & Bucht 2011), often because of heavy pollution of these streams (Bjur 1988). In the long term, lost rivers lead to loss of ecosystem functions and services in the urban environment (Meyer & Wallace 2001).

Blue-green infrastructure

Blue-green infrastructure is a concept for landscape planning where urban stormwater is controlled in a decentralised manner with vegetated structures (Liao et al. 2017, O'Donnell et al. 2017). There are a vast number of concepts to describe decentralised and sustainable drainage of stormwater through vegetated measures, e.g. best management practises (BMPs), low impact development (LID), sustainable (urban) drainage systems (SuDS/SUDS), green infrastructure (GI), and water sensitive urban design (WSUD) (Fletcher et al. 2015, see also **Paper V**). The concept blue-green infrastructure is chosen in this work, as it emphasises the importance of both *blue* (water) and *green* (vegetation) and the interaction between them. The word *infrastructure* underlines the fact that different elements need to be interlinked to work as a connected web of measures (Lennon 2015). Water obviously follows flow paths, natural or constructed, but urban ecological networks and connectivity is also important in perspective of ecology (Ahern 2013), where it benefits spread of flora and fauna between the different green elements. The connected parts are more than the sum of the single elements. Sandström (2002) similarly chose the concept green infrastructure, instead of the traditionally more commonly used green space, to signal the multiple purpose of urban green spaces. The word infrastructure gives the concept the same dignity as other kinds of (technological) infrastructure (Sandström 2002, Lennon 2015). In countries with a neoliberal agenda, it is emphasised that such measures complement rather than prevent economic development (Matthews et al. 2015). Every element of blue-green infrastructure is in itself a nature-based solution (NBS) and mimics natural ways to handle water (EC 2015). The economic benefits of such solutions have been put forward by the European Commission as well as through research (ibid., Ossa-Moreno et al. 2017).

Stahre (2006) categorises the different elements of blue-green infrastructure depending on their role in the stormwater control system and on the stakeholder that can allocate space for them (Figure 2). Most upstream, source control is used to describe small scale facilities, like green roofs, pervious pavements and local ponds, typically on private land. On public land, onsite control measures for detention, infiltration and evaporation, such as soakaways, special surfaces for temporary flooding, and smaller ponds, are found. Water from these structures are retained in channels, swales, and other structures for slow transport. Larger retention ponds, lakes and wetlands serve as downstream control.

Green spaces are important in urban areas for many different reasons (Sandström 2002): recreation, maintenance of biodiversity, city structure, cultural identity, environmental quality of the urban area, and as biological solutions to technical problems in urban areas. Swedish cities are recommended by the National Board of Housing, Building and Planning to develop a green plan where urban green spaces are identified together with their value to the public (ibid.). This plan should be a part of the mandatory structure plan. However, Sandström (2002) showed that these

URBAN, PLUVIAL FLOODING

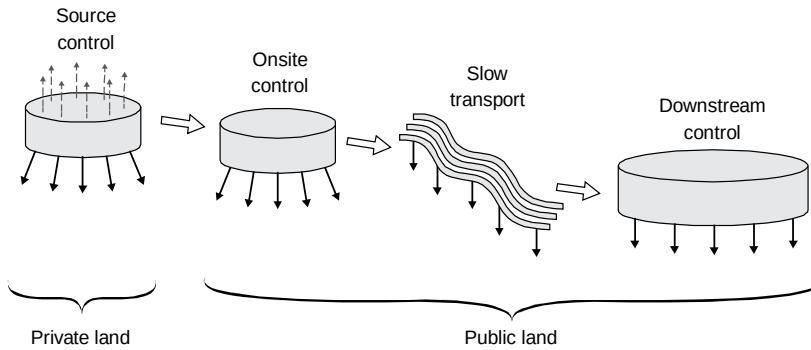


Figure 2. Four categories of elements of blue-green infrastructure. On private land and most upstream, source control with small scale facilities are placed. On public land, onsite control measures for detention, infiltration and evaporation are constructed. Water from these structures are retained in structures for slow transport. Downstream control is achieved by larger retention ponds, lakes and wetlands. Adapted from Stahre (2006).

plans do not take into consideration the multiple purposes of green spaces in the urban environment. The relation between urban green spaces and water is only to a limited degree mentioned and discussed in the evaluated plans (*ibid.*). The European Commission defines green infrastructure as “a strategically planned network of high quality natural and semi-natural areas with other environmental features, which is designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings.” (EC 2013). This definition does not explicitly include water. The US Environmental Protection Agency does the opposite and use green infrastructure as a more narrow, water focused concept to describe vegetated, stormwater technologies. They claim that “green infrastructure is a cost-effective, resilient approach to managing wet weather impacts that provides many community benefits” and exemplifies with technologies like rain gardens, bios-wales, downspout disconnection, urban tree canopy, green streets, and rainwater harvesting (US EPA 2018).

Often the values created in urban green spaces and natural environments are named ecosystem services. The 2005 Millennium Ecosystem Assessment (MA 2005) defines these services as “the benefits people obtain from ecosystems” and divides them into four groups: supporting services, which are necessary for all other ecosystem services (e.g. soil formation and nutrient cycling), provisioning services, which are products obtained (e.g. food, timber, and fuel), regulating services, which are ecosystem processes that can regulate the local environment (e.g. heat regulation and pest control), and cultural services, which are nonmaterial benefits (e.g. recreation and aesthetic benefits). Flood control by blue-green infrastructure is seen as a regulating ecosystem service.

Blue-green infrastructure influences the urban hydrology in different ways, depending on the chosen solution (Figure 3). Green roofs and other green surfaces

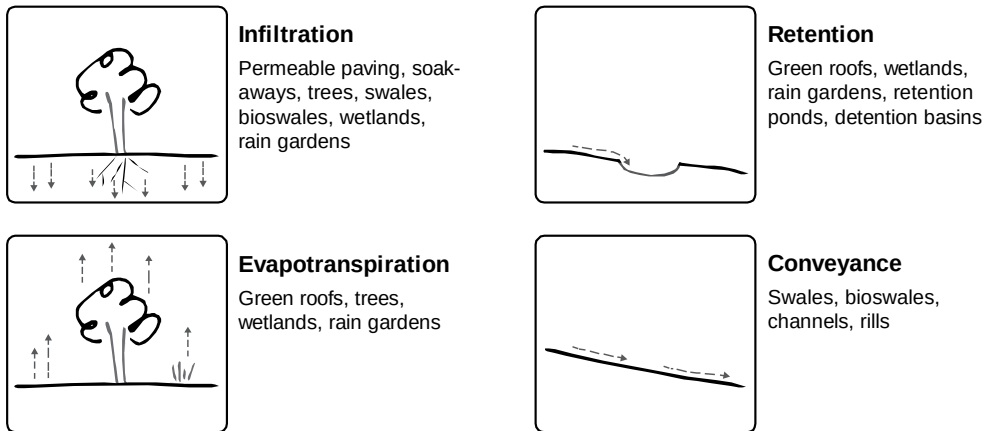


Figure 3. Hydrological features of blue-green infrastructure, including infiltration from different surface and basins, evapotranspiration from vegetation, retention in ponds, basins and on green roofs, and slow conveyance in swales and channels.

reduce the share of sealed surfaces and allow for infiltration. They store rainwater and delay runoff, leading to extensive evapotranspiration from the surface. Pervious pavements and soakaways provide infiltration through the soil. Tree canopy intercepts rainfall, while their tree pits provide infiltration. Retention ponds and detention basins store rainwater and lower discharge to downstream recipients. Wetlands retain water, which later evapotranspire, infiltrate or discharge. Rain gardens function in a similar way, only at smaller scale, but, in opposite to wetlands, they usually dry out after each rain. Channels and rills convey surface water. Swales and bioswales ensure slow conveyance and some infiltration. Surfaces for temporary flooding, like concave green spaces, detain surface runoff during heavy rainfall. As none of the solutions are optimal for all different rainfall intensities, it is preferred that they are used in combination, in a so-called treatment train. For a detailed description of different solutions, see for instance the SuDS Manual by Woods Ballard et al. (2015).

Several studies have indicated that different solutions used in blue-green infrastructure are beneficial for flood reduction, like storage ponds (Villarreal et al. 2004), concave green spaces (Liu et al. 2014), green roofs (Qin et al. 2013), pervious pavements (Qin et al. 2013, Liu et al. 2014, Zahmatkesh et al. 2014), and infiltration basins (Stewart & Hytiris 2008). A combination of different measures is recommended to achieve maximal effects for different kinds of rainfall events (Qin et al. 2013, Liu et al. 2014). Zölch et al. (2017) have on the other hand shown with a rather extreme scenario, where all roofs in an area are hypothetically made green, that green roofs alone only reduce the runoff by approximately 20% of the total precipitation for events with 2- and 5-years return period. Extensive planting of trees reduce runoff even less, by approximately 5% for the same events (ibid.). Torgersen

(2015) has shown that precipitation events prior to the extreme events have a significant impact on the number of reported insurance claims after urban flooding. The flow regime of large ponds and wetlands has been criticised, as it prolongs the time of extensive discharge to downstream recipients (Roesner et al. 2001) and such structures might even increase the flood risk downstream if the peak flow coincides with peak flows from other areas. For events up to 10-years return period, however, Villarreal et al. (2004) has shown that blue-green infrastructure in Augustenborg can handle large storm events by detention in ponds even during wet initial conditions.

Stormwater control measures are known for their ability to treat stormwater from polluting particles and dissolved compounds. Ponds are used for settlement of particles (Marsalek & Marsalek 1997) and for properly designed ponds expected treatment effects are 70% for particle-bound pollutants (Blecken 2016). The effect is however diverse, where for instance reduction rates of phosphorous have been reported from as low as 2% to up to 92% in Sweden (*ibid.*). Urban wetlands can also reduce suspended solids and dissolved pollutants by a combination of physical, biological and chemical processes (Greenway 2004). Caution must be taken as stormwater carries heavy metals from the urban fabric (Shaheen 1975). These metals are not treated or degraded but detained by the stormwater control measures (Blecken 2016). They will therefore stay in the sediment of the control measure, in more or less mobile forms (Marsalek & Marsalek 1997), and potentially leak to the downstream recipient during intense rainfall, maintenance or changed acidity.

The development of urban drainage over time has necessitated more and more perspectives to be included in parallel, from early focus on drainage and hygiene to amenity, climate change adaptation and resilience thinking (Brown et al. 2009). There is today a need for stakeholders to understand several disciplines or perspectives in parallel, such as hydrology, ecology, landscape architecture, urban planning, etc. (Brown et al. 2009), not the least when planning and designing blue-green infrastructures. Blue-green infrastructure is highly complex (Hoang & Fenner 2016) and it is a challenge how to best organise management among a diverse group of professionals. Geldof (2007) suggested the Three Point Approach (3PA) as a tool for how to move from only focusing on design standards for rainfall events that occur with a return period of 1 in 10 years (first point) to including extreme rainfall events (second point), and at the same time consider the impact on every-day life (third point). Fratini et al. (2012) found this tool useful in discussions with several stakeholders. The tool has been further developed as a tool for water balance calculations by Lerer et al. (2016).

Urban land use is a central aspect of spatial planning, getting more important with urban densification. Starting in the research debate on agricultural strategies to improve biodiversity without crop yield decrease, Lin and Fuller (2013) adapted the concept of land sharing and land sparing to the urban context. With land sharing, areas for human activity is spatially mixed with areas for high biodiversity and with land sparing they are separated, leading to less, but more concentrated area for both.

Land sparing leads to higher biodiversity (Sushinsky et al. 2013), and if the goal is to preserve a high diversity of species globally, land sparing might therefore be preferred. It should however be mentioned, that the concepts land sharing and land sparing are limited to densification within the same extent of an urban area. It does not consider the possibility to urbanise by expansion of urban land, i.e. urban sprawl. As argued by Stott et al. (2015), the structure and quality of ecosystem services vary for different urban green spaces. Similarly, the water retaining capacity varies depending on the shape of urban green spaces and their hydrological link to the surroundings. The consequences of the land sharing or land sparing strategy on hydrology have not been investigated yet.

Transition theory

Blue-green infrastructure is a fairly new technology that goes outside the currently dominating socio-technological structure for stormwater management. Research has shown that barriers for transition is institutional rather than technical (Brown & Farrelly 2009a). In **Paper IV**, transition theory with a multi-level perspective is used as an analytical tool to explore barriers and drivers that may exist in relation to an altered management of stormwater in Sweden. Within transition theory, socio-technological systems, in this case the stormwater management system, are seen as composed of three constellations: *regime*, *niche* and *niche-regime*. Surrounding these is the *landscape* that forms the prerequisites for the *system* (de Haan & Rotmans 2011). The three constellations and their surrounding landscape are shown in Figure 4. While Rotmans et al. (2001) relate the levels to bureaucratic levels (macro, meso, and micro level) or nested hierarchies, the levels are in this work perceived as including organisational, technical as well as social systems as suggested by Geels (2011). In the following section the features of the multi-level perspective are briefly explained and thereafter the process of change according to transition theory is described.

The *regime* dominates the system and is the way that societal needs are met (de Haan & Rotmans 2011). A regime includes institutions, technologies, practical applications and social relationships (Geels 2002). The regime is the most powerful constellation of the system (de Haan & Rotmans 2011). In Sweden, the current regime of urban drainage management consists of a pipe-bound infrastructure with a centralised management. Several actors are involved in developing and maintaining it (Cettner et al. 2012). A shift to a new regime is more than just an evolutionary transformation of a previous regime. There is a significant difference before and after a regime shift. For instance, to change from combined to separate sewers is an evolutionary transformation, while the change from pre-sewered cities to sewerred cities can be considered as a transition to a new regime (Ashley et al. 2011).

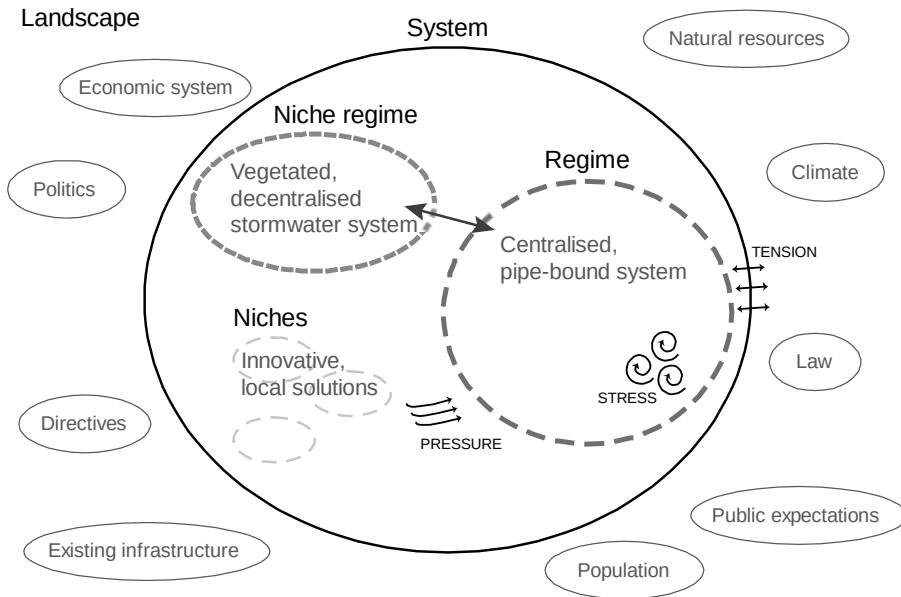


Figure 4. Transition theory according to Ashley et al (2011) and de Haan & Rotmans (2011) as applied to urban drainage in Sweden.

A *niche* is a system that only meets certain, specific societal needs (de Haan & Rotmans 2011). The niche level is mainly referred to where emerging innovations are developed that are fundamentally different from solutions at the regime level (Geels 2011).

A *niche-regime* is a regime that is not currently dominating, while it has significant power to compete with the regime for the functioning of the system (de Haan & Rotmans 2011). Thus, a niche-regime is somewhere between niches and the regime in strength.

The *landscape* represents the wider context, e.g. legal systems, demography, economy and the natural environment, that in a long-term perspective is able to influence and affect the development of the practices at regime, niche-regime and niche levels (Geels 2002, Geels 2011, Koppenjan et al. 2012).

A central idea of the transition theory is that change emerges from niche through alternative solutions to niche-regime to displaced or replaced regime, but a regime can also be influenced by actions and ideas emerging from landscape level (Koppenjan et al. 2012, Geels 2011). The challenges of the regime emerge from the dispersal of new social norms concerning how to solve a problem, know-how and motivation that alternative solutions bring with them when developed and implemented at the niche level (van de Bruges et al. 2005, de Haan & Rotmans 2011, Ashley et al. 2011, Farrelly & Brown 2011).

Drivers for this type of socio-technical transition have been divided into three categories: *pressure*, *stress*, and *tensions* (de Haan & Rotmans 2011), see Figure 4. Pressure comes from alternative technologies that become viable competitors to the regime. Stress emerges when the regime is inadequate or internally inconsistent in meeting the needs of the system. Tension is when the system compromises in its relation to its natural or social environment. The tensions can either be structural, related to physical aspects of the regime, legal or cultural, related to cognitive or discursive aspects of the regime (ibid.). Structural tensions are more frequently related to pressures from the landscape level whereas the cultural tensions can emerge from both niche and landscape level (Ashley et al. 2011).

Due to entrenched technological path dependency and cognitive lock-in, actors may be unable or hindered to implement new solutions (Bettini et al. 2015). Such implementation barriers have different origins and can be technological, legal, organisational, financial, social, educational or related to political will (Holtz et al. 2008, Brown & Farrelly 2009a,b, van de Meene et al. 2009, Cettner et al. 2013, Mguni et al. 2015). As a consequence, a transformation of a regime must consist of both physical and administrative changes in the regime (Bettini et al. 2015) and change usually has to occur at multiple levels for a regime to alter (Geels 2002).

Flood risk management

This section is mainly based on **Paper I**, which serves as a background for the thesis and where the flood risk management framework below is presented.

There are a vast number of definitions of risk (Persson 2007) with meanings and dimensions related to safety as well as environmental, social, and economical issues (Gouldby & Samuels 2009). A single, standardised definition would never satisfy everyone (ibid.). However, often the definitions have several aspects in common, i.e. that there is an uncertainty about what will happen in the future, that the future can be influenced and that the outcome of a future event will impact humans. Risk is also often related to a preferred outcome and in this work, risk is seen as a deviation from a preferred and expected pathway of development (**Paper I**).

Three other common definitions of risk could be mentioned. 1) Risk is often seen as a function of probability that something negative could happen and the consequences of such an outcome (Gouldby & Samuels 2009). 2) Crichton's Risk Triangle (Crichton 2008) includes three components: hazard, exposure, and vulnerability. Hazard is the phenomenon or activity that may cause loss of life, health impacts, damage, disruption, or environmental degradation (UNISDR 2016). Exposure is the situation of people or assets in areas that might be affected by a hazard (UNISDR 2016) and is a necessary, but not sufficient, determinant of risk (Cardona et al. 2012). Vulnerability is the conditions that determine whether an individual, an asset,

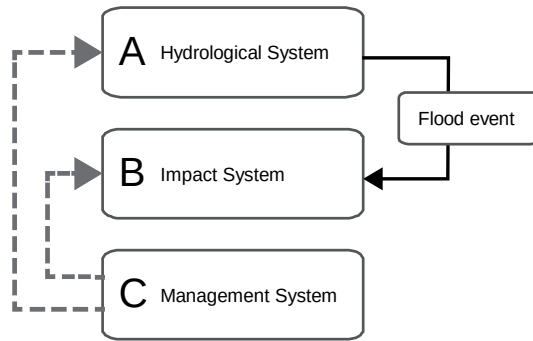


Figure 5. The three systems involved in urban flood risk management: A) the hydrological system, B) the impact system, and C) the management system.

the society, or a system is susceptible for hazardous impacts (UNISDR 2016). To be vulnerable to extreme events, one must be exposed (Cardona et al. 2012). According to Crichton, there is no risk if not all three components are present (Crichton 2008). 3) Risk can also be understood through the Source-Pathway-Receptor-Consequence model (Gouldby & Samuels 2009). The source is the hazard (e.g. rainfall or waves) that through a pathway (e.g. flood plain inundation) hits a receptor (e.g. people) and has some consequences (e.g. loss of life). A disaster might be seen as the state where risk becomes materialised, i.e. becomes real (Cardona et al. 2012). While risk definitions often focus on single or multiple events that might have a negative impact, the definition used in this work, where risk is a possible, negative deviation from a preferred pathway of development, focus is rather on the preferred future. Risk management might thus directly be linked to the work with sustainable development (**Paper I**), which is not a steady state of harmony, but an ongoing process of change (Brundtland Commission 1987).

By flood risk management, flood risk is assessed, and measures are taken to reduce negative outcome of a possible, future flood event. Urban flood risk management can be described as a system of systems (Figure 5), as presented in **Paper I**. The hydrological system (A) is the physical system where the water flows through the urban landscape, intentionally or not. The impact system (B) includes all parts of the society that are affected detrimentally during a flood event. The management system (C) is a social system that includes the features of society that deal with flood management to decrease the negative effect of a flood event. During an event, the impact system is affected by processes governed by the hydrological system (arrow from A to B). These negative effects are to be reduced by the management system, both in the long term and in the short term, by reducing the society's vulnerability to flooding (arrow from C to B). Processes in the management system can also impact the hydrological system (arrow from C to A), especially in the long term, by construction, control and improvement of the urban drainage system and water-courses, including blue-green infrastructure, and changes in elevation and land use

in the urban landscape. Such changes will have an impact on the severity of coming flood events.

In Europe, the EU Water Framework Directive (WFD) (Directive 2000/60/EC) and the EU Floods Directive (FD) (Directive 2007/60/EC) have forced the countries to work more extensively with the urban waters. The WFD commits all member states to achieve good qualitative and quantitative status of inland surface waters, transitional waters, coastal waters and groundwater. The FD calls for actions to mitigate flood risk by first making risk assessments in two steps and then develop flood risk management plans. Implicitly the FD focuses on riverine floods. However, pluvial floods, which “may be excluded” in the work with the FD, also constitute a formidable threat to cities around the world. In the UK, for instance, pluvial flood risk accounts for approximately one-third of all flood risk (Houston et al. 2011), indicating that it is important to include pluvial flooding in flood risk assessments. In the US, pluvial flooding has only recently been included in a more comprehensive way in a new estimate of flood risk (Wing et al. 2018). In Sweden, one of the first outcomes of the FD implementation was a flood risk mapping in 2011, where 18 areas were identified as considerably vulnerable, followed by a revision in 2016–2017, where also coastal flooding was included (MSB 2018). Pluvial flooding was not included in the national flood risk mapping, but the Swedish Civil Contingencies Agency (MSB) has produced a guide for how such mapping could be done by the municipalities (MSB 2017). MSB is responsible for issues concerning civil protection, public safety, emergency management and civil defence in Sweden (MSB 2018). Much of the work with flood risk management is however led by the municipalities. The FD was implemented in Sweden as a decree and not as a law, giving some unclarities regarding the municipal role in its implementation, as they cannot be forced to act through a decree (Thorsteinsson & Larsson 2012). Together, the FD and the WFD call for new ways to manage urban stormwater, preferably with a holistic view, including both water pollution and flood risk mitigation, however this is not explicitly spelled out in the directives.

In **Paper I** five challenges related to flood risk management from a transdisciplinary view were identified: 1) to build flood resilient cities, while not forgetting to meet other climate change related impacts such as water scarcity, drought, and heat waves in the municipal planning, 2) to jointly consider the water, energy, land use, transportation, and socioeconomic nexus from a multi-stakeholder perspective, 3) to use flexible flood protective measures in the view of uncertainty regarding future climate, 4) to solve questions regarding responsibilities and improved communication between stakeholders and authorities, and 5) to secure critical infrastructures. Blue-green infrastructure was identified as a key concept to meet challenge number 1 and 3 above and is also closely related to challenge number 4.

Risk and resilience

The resilience concept became known within ecology by Holling, when he criticised the idea of a single, stable equilibrium for ecosystems. According to his definition, “resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb change of state variables, driving variables, and parameters, and still persist” (Holling 1973). He emphasises the ability of an ecosystem to persist, despite stress on central functions of the ecosystem. His definition is often mentioned also in hydrology, but other disciplines have used the concept before him, for instance in psychology. Olsson et al. (2015) mentions several interpretations of the word, like bouncing, leaping, rebounding, human resourcefulness, elasticity, and resistance. The concept was introduced in risk management, with the article by Berkes in 2007 (Liao 2012), and has gained increasing popularity in the scientific literature as well as among practitioners.

According to Olsson et al. (2015), the interpretations of resilience can be categorised by two important differences: whether resilience is regarded as a descriptive (neutral) or a prescriptive (positive) concept, and whether the long-term changes are included in the concept or not, i.e. if the system bounces back to its former state or if some kind of transformation is included. Olsson et al. (2015) give examples of articles where the concept is defined either descriptively or prescriptively and that sees a resilient system as either a system that bounces back after stress or as a system that can bounce back and transform after stress. Both Perrings (1998) and Holling (1973) see a resilient system as one that only bounces back to its former state, but Perrings uses resilience as a normative concept. It is most common to use resilience in a prescriptive or normative way, which differs from the way Holling used the concept (Olsson et al. 2015). Both Walker et al. (2006) and Folke et al. (2010) see a resilient system as a system that can bounce back and transform, but it is to be noted that while Walker et al. (2006) is descriptive, Folke et al. (2010) is normative. Interestingly, Walker and Folke are co-authors on each other's papers.

Within flood risk management, the concept is interpreted as how well a system, e.g. the city, can handle a flood event. For instance, Liao (2012) defines resilience as follows: “Urban resilience to floods is defined as a city's capacity to tolerate flooding and to reorganize should physical damage and socioeconomic disruption occur, so as to prevent deaths and injuries and maintain current socioeconomic identity.” Liao here emphasises that resilience is about the societal reaction to a flood event. According to her, experience of minor flood events prepares the society to better handle major flood events. The smaller events offer a possibility to prepare for coming, larger events: “[Urban resilience to floods] derives from living with periodic floods as learning opportunities to prepare the city for extreme ones” (Liao, 2012). Liao's definition of resilience is thus normative—more resilience is always better than less resilience. Similar thoughts about preparation for major events by experience of minor events are brought forward also by others. Crichton (2008) argues that flood vulnerability in Paris has increased in the last 100 years, as people

seem to have forgotten about the flood risk because of construction of four upstream reservoirs. The Seine is now more narrow and sensitive buildings, like schools and hospitals, have been built on the former flood plain (Crichton 2008). In the Netherlands similar problems because of extensive flood protection along the coastline are seen. Smits et al. (2006) argue that these flood defences have resulted in more people living in areas with high flood risk, despite the original efforts to lower the flow risk. In Japan, a new strategy to restore storage in the upstream areas of the river catchments has been used since 2001, as the former strategy to defeat nature with concrete did not work (Crichton 2008).

In this work, resilience is seen as the capacity of a society to manage risk, not diverting from the preferred and expected trajectory of development over time, not crossing human and environmental boundaries (see **Paper I**). Resilience is thus both linked to risk and sustainability and can be increased both through construction of measures to lower risk and by increased awareness, societal preparedness, reduced vulnerability of certain groups and other measures for continuous, societal development. The aim for resilience to urban flooding is fast recovery from flooding and restoration to good living conditions. At the same time, long-term strategies are needed to facilitate cost-effective and rapid implementation of integrated flood management. Sustainability should not only be achieved economically, but also socially and environmentally (Brundtland Commission 1987). Cities should not wait for a larger flood event or a large-scale catastrophe to act. Instead, city planners need to study front-runner cities that are dealing with flood challenges. Learning from the experiences of others, and ourselves, is of crucial importance and saves energy, resources, and time.

Decision-making under great uncertainty

Urban planners, engineers, and other practitioners that are involved in flood risk management, must handle great uncertainties about both current and future flood risk. According to Gouldby & Samuels (2009), uncertainty can arise in three different ways:

- *Knowledge uncertainty* is when we lack knowledge about how the physical world behaves and can also be referred to as epistemic, functional, internal, or subjective uncertainty or as incompleteness,
- *Natural variability* is the inherent variability in the real world that cannot be predicted and can also be referred to as aleatory, external, inherent, objective, random, stochastic, irreducible, fundamental, or “real world” uncertainty,
- *Decision uncertainty* is related to the complexity of values and objectives from social and organisational perspective.

Current flood risk is mainly due to natural variability and knowledge uncertainty, while future flood risk includes all three types of uncertainties: Decision uncertainty, related to decisions impacting urban development and climate change, knowledge uncertainties, related to what effect such development and change will have on urban, pluvial flood risk and the natural variability in rainfall patterns. Altogether these uncertainties make decision-making more complex, which needs to be handled in flood risk management and urban planning. In addition to these uncertainties, Refsgaard et al. (2013) list *ambiguity*. Ambiguity results from different understanding of a system due to differences in professional backgrounds and values. While some others combine knowledge uncertainty and ambiguity, as ambiguity will be reduced with more knowledge, Refsgaard et al. (2013) argue that this is not the case. More knowledge does not always converge to a single truth (ibid.). In **Paper V**, some problems related to ambiguity are discussed.

In design of stormwater systems, changed rainfall intensities due to climate change is often only considered by adding more rain to the design rain (Willems 2013, Knighton & Walter 2016). This approach is however criticised, as uncertainty about future precipitation and urban land use calls for more elaborated strategies. Hallegatte (2009) proposes the following strategies to handle large uncertainties in urban planning due to climate change.

- No-regret: The solution is beneficial even in absence of climate change. Multiple problems are solved with one solution, like energy saving or urban green in combination with climate change adaptation.
- Reversible strategies: Flexible solutions that can be adjusted depending on the outcome. For instance, it is much easier to wait with urbanisation of an area than to first develop and then retreat.
- Safety margin: Make a little bigger while designing new infrastructure. Be over pessimistic.
- Build resilience (soft strategies): Creation of institutes that can manage risks: e.g. insurance schemes to cover losses, early warning systems, etc.
- Reduce decision-making time horizons: Construct cheap houses that are made to be rebuilt after some time.

Information sharing in urban planning

With geographic information systems (GIS), spatial data can be managed, visualised, analysed and used for modelling to serve spatial planning and functions like map overlay, connectivity measurement, and buffering (Yeh 2005). GIS can also be integrated in decision support systems (Zerger & Wealands 2004) and is efficient in data retrieval, query, and mapping (Yeh 2005).

Efficient urban planning and flood risk management requires efficient information sharing. Spatial data infrastructure (SDI) works as an infrastructure for sharing geographic data and metadata and ensures that all stakeholders have access to the same updated, detailed, high-quality data. Web-based solutions make data and information on a detailed level available to responsible parties, while the public can get access to up-to-date information. SDI ensures that GIS data sets can be used also by others than the data providing organisation as well as for other purposes than they originally were meant for. By database writing permissions set by the responsible data holder, stakeholders can contribute with data to different datasets.

Community mapping offers the public the possibility to contribute with data to a common database. In Sweden community mapping is for instance used by the Swedish Species Observation System to collect observations of species from the public.

Despite the usefulness of GIS data, the use is often limited in contemporary planning and many planners and engineers lack in-depth knowledge of GIS. In **Paper V**, the need for a comprehensive use of GIS in the planning of blue-green infrastructure is evaluated and a framework for GIS data collection, management and use is presented.

Study area

Malmö in southern Sweden is at the centre of this work. For the analysis of flood mechanisms and characteristics on city scale (**Paper II**), Malmö inside the Outer Ring is used as study area. To study flooding and blue-green infrastructure (**Paper III**), the study area is focused on one district: Augustenborg Eco-City, an area that was retrofitted with stormwater control measures in early 00s. For the interview studies of transition to blue-green infrastructure regime (**Paper IV**) and for the framework development (**Paper V**), the study area is zoomed out to include municipalities and water utilities in the region of Scania, including Helsingborg, Lund, Tomelilla, and Simrishamn, besides Malmö. The included study areas are shown in Figure 6. **Paper I** is not related to any study areas but gives a general perspective of flood risk management.

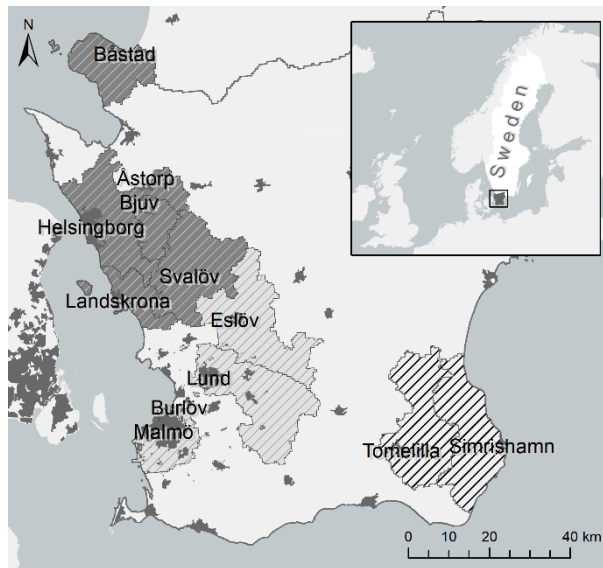


Figure 6. Malmö provides the study areas for both **Paper II** and **Paper III**. Municipalities covered by the water utility companies in **Paper IV**, NSVA in the north-west (dark grey) include Helsingborg, and VA Syd in the south-west (light grey) include Malmö and Lund. Officials in **Paper V** represent VA Syd, Malmö, Tomelilla and Simrishamn.

City of Malmö

The city of Malmö, Sweden, was selected as study site since, in the Scandinavian context, Malmö is a large city, where there have been several flood events in recent years, including the extreme event in 2014. Like in many other cities, the more densely built areas have sewer systems where stormwater and sewerage are drained with one single pipe (combined system), leading to risk of basement flooding. Malmö is thus representative for Scandinavian cities and many other cities in the developed world. Good quality data on flood extent, precipitation, topography, sewerage system, etc. are available. Malmö is also well-known within the field of urban hydrology, as the city was an early starter in the work with integrated water management and blue-green infrastructure (Niemczynowicz 1999, Stahre 2008).

Augustenborg Eco-City

In Augustenborg, a 30 hectares residential area in Malmö, stormwater is controlled by blue-green infrastructure consisting of detention in ponds and areas for temporary inundation, infiltration on green roofs, lawns and parking lots, as well as slow transport in swales, ditches and channels. Most of the stormwater drainage was disconnected from the old combined sewers that are now only used for wastewater, while the main street through the area still is drained through a pipe. The retrofitted blue-green infrastructure was constructed by the end of the 1990s by VA Syd (utility company) and MKB (public housing company) as a part of the project called Eco-City Augustenborg. For a detailed description of the blue-green infrastructure in Augustenborg, see **Paper III**. About 3 000 people live in the area in 3–6 storeys apartment blocks built in 1948–1952. The area continues to be developed and in 2016 the area was densified with a 14-storeys building.

Municipalities and water utilities in Scania

For the two interview studies, the study area was zoomed out to include other municipalities and water utilities in the region of Scania. Swedish municipalities are legally responsible for stormwater management on public land. The practical responsibility is frequently delegated to public water utilities which often are co-owned by several municipalities. In the first interview study (**Paper IV**), on transition to blue-green infrastructure regime, Malmö and Helsingborg were used as cases. The two municipalities use two different water utility companies, VA Syd (Malmö) and NSVA (Helsingborg), to provide stormwater management and water treatment services to a total of 730 000 persons (Figure 6). Malmö (330 000 inhabitants) and Helsingborg (140 000 inhabitants), are the two largest cities in the region and have a long experience of working with blue-green infrastructure.

Interviews for the framework development (**Paper V**) was done with municipal and utility staff from Malmö, Lund, Tomelilla, and Simrishamn, as well as one GIS researcher. While Malmö and Lund (122 000 inhabitants) are larger municipalities, Tomelilla and Simrishamn are two smaller municipalities in south-eastern Scania with 13 400 and 19 400 inhabitants respectively. And while the stormwater management and water treatment services are provided by VA Syd in Malmö and Lund, these services are provided by the municipal departments in Tomelilla and Simrishamn. This means that the number of people working with stormwater management are much fewer in Tomelilla and Simrishamn compared to Malmö and Lund. The GIS responsible official that was interviewed is shared between the two smaller municipalities.

Methods

This chapter gives an overview of the methods used in the appended papers. Further details on the methods and the data used are found in the papers.

Insurance claims as a measure of flood severity

One of the main purposes of this work is to analyse the physical mechanisms and characteristics of urban, pluvial flooding (**Paper II**). Flood damage through registered insurance claims are used to evaluate the spatial distribution of flood risk related to these mechanisms and characteristics. Flood claims are used as a measure of spatial extent and severity of different flood events, and as a representation for flood risk in different places, which can be related to all three sides of the Crichton's Risk Triangle (Crichton 2008), i.e. hazard, exposure, and vulnerability. The vulnerability and exposure of individual households are however not assessed as the study focuses on city-scale patterns. Insurance claims were also used in **Paper III** as a proxy for flood risk to evaluate the flood risk reduction achieved with blue-green infrastructure.

Insurance claim data have been used for various other studies to analyse the relation between rainfall and pluvial flooding in Denmark (Zhou et al. 2013, Spekkers, Zhou et al. 2013), and in the Netherlands (Spekkers, Kok et al. 2013, Bouwens et al. 2018). One catastrophic event might lead to many claims. For statistical analyses of insurance data, where independent random variables are needed, single claims must, according to Smith & Goodman (2000) be aggregated into common losses for each event. However, in this study, where the hydrological process behind the losses is investigated, the individual claims provide essential information about the spatial extent of the damage.

Flow path analysis

In **Paper II**, the minor and major drainage systems of Malmö were investigated. The major system was derived from a simple analysis of the topography where the flow from an eight-direction flow model (Jenson & Domingue 1988) is accumulated into each cell. No validation of the analysis was done, but it was compared with the minor system, delivered as an outline of the main sewers by VA Syd (water utility company). Old maps from Malmö was studied in relation to the derived minor and major system.

Single event as a case

The severe flood event on the 31 August 2014 in Malmö is used as a special case in both **Paper II** and **III**. This was the biggest rainfall event since measurements started in Malmö in the late 1800s and led to severe flooding in most of the city as well as in neighbouring villages and in some parts of Copenhagen, Denmark. For durations longer than two hours the rain event exceeds the 100-year return period. The event became a stress test to the urban environment and drainage system and is therefore of research interest. While such intense events are rare, similar events can happen in any city within the same climatic zone, independent of their average, annual rainfall (Bengtsson & Rana 2014), making them meaningful to learn from. As the interviews for **Paper IV** were conducted after the event, also the results from this study are affected by the event, because of its big impact on the society.

Research on extreme events are somewhat complicated, as mentioned in the theoretical background. Still, recent cases of severe flooding are the only way forward if we want to make research based on empirical material and not only based on models. Investigations of a single event might be fruitful in many cases, but also limits the relevance for other places. In this work, the extreme event in 2014 has

been complemented with data from other major and minor events to partly overcome this problem.

Comparative analysis

In **Paper III**, flood risk in Augustenborg was compared with flood risk in five nearby areas, Lindgatan, Lönngården, Norra Sofielund, Södra Sofielund, and Persborg. The areas were selected as they are similar to Augustenborg in several ways, i.e. land use, building coverage, time of urbanisation, and original sewer system (combined). Blue-green infrastructure has only been implemented in Augustenborg, while the other areas still mainly have combined systems, which make them suitable for comparison with Augustenborg in this study. Lindgatan is an exception, as the combined system has been reconstructed with a separate system here.

Flood magnitude was defined as the number of flooded properties per hectare (NFP/ha). This measure was used to compare the flood risk in Augustenborg with the other areas. A bootstrap resampling technique was used to statistically evaluate long-term differences between flood magnitudes in the retrofitted area Augustenborg in comparison to the five nearby areas.

Interviews

Semi-structured interviews were made with staff in water utility companies and municipal water and planning offices. Interviews were used both to better understand the barriers and drivers for implementation of blue-green infrastructure (**Paper IV**) and to develop a framework for data use in city planning with blue-green infrastructure (**Paper V**). For the first purpose, water engineers, ecologists, landscape architects and planners were interviewed (**Paper IV**), and for the latter purpose, water engineers, ecologists, planners, and GIS experts were interviewed (**Paper V**). Two of the interviewees worked with GIS data collection, management and support (a researcher and one of the officials).

The interviewed persons work at different municipal offices, such as the environmental office and the planning office, and have a varied academic background. For both studies, a majority though have a background in natural and technical sciences. In total, 20 persons were interviewed in the first study (**Paper IV**) and 6 persons in the second study (**Paper V**).

Multidisciplinary research

In both **Paper I** and **V**, mutual exchange of disciplinary knowledge was used to better understand a certain topic, i.e. flood risk management and GIS in urban planning respectively. In both studies, a series of discussion and brainstorming sessions with the involved researchers were used to understand the topic from different perspectives and to find the links between the different perspectives. In the case of **Paper V**, these sessions were supplemented with interviews with practitioners, because of the applied nature of the topic, while a more theoretical approach was used in **Paper I**.

Results

The main findings are presented shortly in this chapter. Further details are found in the publications. As **Paper I** serves as a background for the thesis, no results from this paper are presented here.

Pluvial, urban flood mechanisms and characteristics (**Paper II**)

Pluvial flooding is the most common type of flooding in Malmö. Only a very few flood claims have been registered during high sea level caused by storms and there is only one minor watercourse in Malmö (Riseberga Brook/Sege Brook), which seems not to be severely affected by riverine flooding. All of the eleven biggest flood events during the 20-year period are caused by local or wide-spread rainfall events. These eleven events account for about 80% of the flood claims reported to the water utility VA Syd and the insurance company Länsförsäkringar Skåne. Three severe, pluvial flood events are presented in the study: 5 July 2007 with 150 and 169 flood claims to VA Syd and Länsförsäkringar Skåne respectively, 14 August 2010 with 210 and 148 flood claims, and 31 August 2014 with 2 109 and 2 649 flood

claims. These flood events were all caused by heavy rainfall distributed over the entire city. The 2010 and 2014 events were intense and with a quick development, while the 2007 event was less intense, but with a long period of pre-event rainfall. The 2014 event was heavier than a 100-year event for durations between 3 and 16 h (average for all stations in Malmö).

There is a relation between large-scale topography and flooding in Malmö. Areas within 100 m from the major system are more than twice as affected by flooding, compared to areas further away. During the severe flood events in 2010 and 2014, areas close to the major system were even more affected by flooding (3.0–4.2 times), compared to areas further away. During such downpours, runoff is quickly directed towards low-lying areas, both through the pipe system and by overland flow. In Malmö, like probably in most other places, the main sewers (minor system) are located under the main overland flow paths (major system), as they follow the topography. The spatial distribution during these two, highly intensive rainfall events (2010 and 2014) were different than during other events, with more flood claims clustered around the main sewers. For the other events, including the 2007 event, the flood claims were more evenly distributed within the city.

The combined system is more exposed to flooding than the separate system. Even if only 31% of the urban land in Malmö is connected to the combined system, 70% of the flood claims are reported from these areas. During the 2010 and 2014 events, the combined system was 3.8–4.2 times more affected by flooding compared to the separate system. Similar figures are found if all flood events are included. The 2007 event shows a different pattern: the combined system areas were only slightly more than twice (2.3 times) as severely affected by flooding during this event, compared to the areas with separate system. One reason why the 2007 event differs from the other events might be the difference in flood causality, where continuous rainfall during the preceding weeks saturated the ground with water. Flooding during this event was therefore less related to type of drainage system. The dataset is biased as more people live in areas with combined system. However, the difference in reported flood claims still exists when adjusted for this bias.

Locally, some flooding is caused by breakdown of the system, e.g. when a sewer pump stops pumping due to system error. On the one hand, the phenomenon with local breakdowns could be seen as unique incidents that are not likely to happen during future flood events. On the other hand, and in reality, it seems inevitable that a few of these unique incidents happen during every flood event.

Flood risk reduction by urban blue-green infrastructure (**Paper III**)

Flood reduction after stormwater retrofit in Augustenborg was evaluated by comparison with five nearby areas (Lindgatan, Lönngården, Norra and Södra Sofielund,

and Persborg) with similar age, land use, and imperviousness as Augustenborg. All five areas have combined sewer systems, corresponding to what Augustenborg had before the blue-green stormwater retrofit, except for Lindgatan that has a separate system. The flood magnitude (number of flooded properties per hectare) was more than 10 times smaller in Augustenborg compared to the other areas both during the extreme 2014 event and during the other events in 2007–2015. The difference was confirmed with a bootstrap analysis and found significant (99% bootstrap confidence interval).

Little data is available from before implementation of the blue-green infrastructure in Augustenborg, but a simple comparison of before and after could be done. This comparison indicated a decreased flood risk after implementation of blue-green infrastructure in Augustenborg.

The flood event on 31 August 2014 is considered as extreme, as more than 80% of the flood claims (2007–2015) were reported this day. The event makes it possible to evaluate the blue-green infrastructure under extreme conditions, which seems to be unique for such an extensive retrofitted area. In Augustenborg, 116 mm was measured, and most of the rainfall (100 mm) fell within 3.5 hours. Compared to the five nearby areas without blue-green infrastructure, the flood magnitude was approximately 10 times lower in Augustenborg during the event, as mentioned before. In Lindgatan, which was the least flooded area, apart from Augustenborg, the flood magnitude was 6.4 times higher than in Augustenborg, while the flood magnitude in the most heavily flooded area, Södra Sofielund, was 18.4 times higher than Augustenborg.

It should be noted that the number of reported flood claims was low in Augustenborg also before the blue-green infrastructure was implemented. However, it seems that the number of reported flood claims has increased in general for the assessed areas for different reasons, while this is not the case for Augustenborg.

Assessment of barriers and drivers for implementation of blue-green solutions in Swedish municipalities (**Paper IV**)

Interviews were conducted with 20 officials working with stormwater management, urban green spaces and planning for the municipalities and the water utility companies of Malmö and Helsingborg. From the interviews, five types of drivers for implementation of blue-green infrastructure were identified, where the focus on ecosystem services, including flood protection, and climate change were most important. All of the interviewees mentioned ecosystem services as a driver. Their suggestion for the most important service is however diverse and includes services as recreational value, delay and treatment of stormwater, biodiversity, and cultural services like aesthetics. The second most mentioned driver was climate change, which

was mentioned by three fourths of the interviewees. The interviews show that there is awareness and knowledge about the changing climate and that the actors need to adapt urban areas to be able to handle the increased precipitation.

Eight types of barriers were identified, all closely related to the current stormwater management regime as understood from the theory, where the whole system, including technical, legal, organisational and other aspects, target the needs in the current regime. It was found that the economy of, the responsibilities within and the organisation of Swedish municipalities and their water utility companies are directed to fulfil the goals of the current, pipe bound stormwater management, rather than widespread implementation of blue-green infrastructure.

The most frequently mentioned barrier is economy, as maintenance costs are uncertain, and the financial structure of Swedish municipalities does not support blue-green infrastructure. It is however interesting that economy also was mentioned as a driver by a third of the interviewees. They argue for instance that replacement of old pipes will be expensive, and that blue-green infrastructure can be a less costly alternative in many cases. Some also mention that it will be costly if flood mitigation related to climate change is done with conventional methods.

In the studied municipalities, there are several players with different skills, knowledge and training involved in the stormwater management chain, from the strategic and overall planning to detail planning for building permits and to private individuals. In the interviews the lack of clarity of roles and responsibilities emerged as an issue. In addition, almost all interviewees mentioned lack of knowledge as a barrier. There is widespread awareness of the idea behind blue-green infrastructure in Sweden, but still knowledge about issues regarding for instance design, inclusion of ecological expertise, and maintenance are lacking.

Legislation and municipal organisation were also mentioned as barriers by many practitioners. They claim that the current legislation in Sweden and the municipal organisation do not support blue-green infrastructure in the planning process. The lack of legal support increases the uncertainty for involved stakeholders and as each municipal department has their own budget, interest and responsibilities, cooperation between them is difficult. Without such cooperation, widespread implementation of blue-green infrastructure is not possible.

A framework for strategic urban planning using blue-green infrastructure and nature-based solutions (**Paper V**)

Blue-green infrastructure incorporates ambitions which, to be fulfilled, require work beyond administrative and disciplinary 'silos', including a more systematic involvement of relevant stakeholders, including citizens. Based on such perspective on planning, the study aimed to better understand the information gaps and to develop

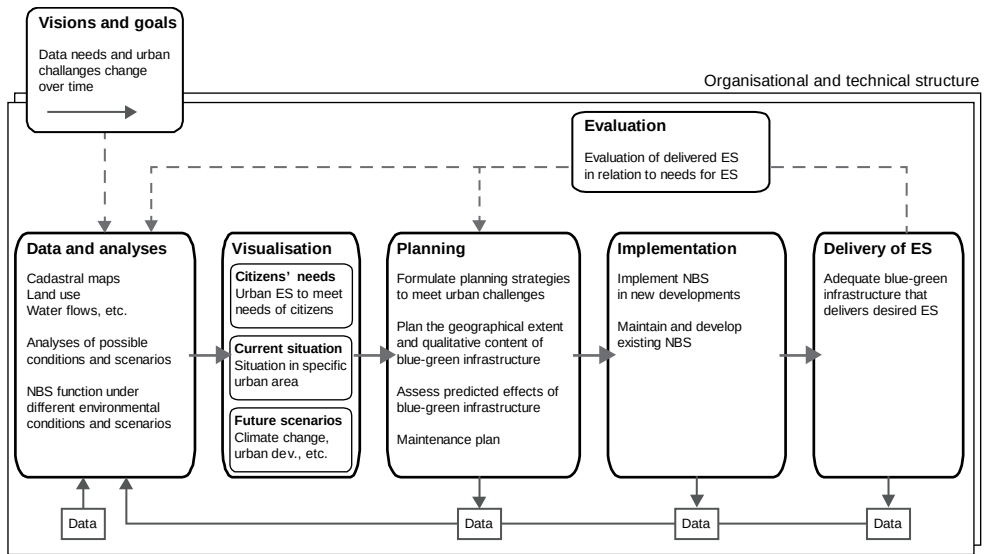


Figure 7. Framework for improved information flows in urban planning of blue-green infrastructure, through the use of nature-based solutions (NBS) and their delivered ecosystem services (ES).

a framework that can support adequate planning of blue-green infrastructure. Different perspectives on data availability and data management in the urban spatial planning of blue-green infrastructure and nature-based solutions (NBS) were assessed in two steps: 1) a number of brainstorming sessions with the authors, and 2) interviews with six practitioners. From these two steps, issues were identified that are relevant for a strategic use of data to aid the development of blue-green infrastructure and the following framework for data use in planning, implementation, and maintenance of blue-green infrastructure was developed (Figure 7).

The framework includes five main steps, from obtaining data to the actual delivery of ecosystem services (ES) from blue-green infrastructure. In the first step, data is collected, stored, maintained and used for analysis of NBS function under different environmental conditions. In the second step, these data and analyses, including information on citizens' needs, the current situation of blue-green infrastructure and related assets in the urban environment, as well as future scenarios such as predicted climate change and urban development, are visualised. In the third step, planning strategies are formulated to meet urban challenges. These strategies must include a plan for the geographical extent of the blue-green infrastructure and its constitutive parts, NBS, as well as a plan for their qualitative content. During the planning step, predicted effects of the blue-green infrastructure on ES of the urban space, including both benefits and trade-offs, should be assessed. To ensure proper long-term functionality of the blue-green infrastructure, all solutions must be included in a maintenance plan. The forth step, i.e. implementation, includes the process from planning,

via design, to construction of NBS. The fifth step shows the main goal, delivery of desired ES by blue-green infrastructure.

Data in the first step should, in addition to new data, ultimately be collected through step three, four and five. These data are often produced in a different format, for instance as CAD data, and therefore need to be converted to GIS data.

Two boxes lie outside the main flow. One shows the importance to evaluate implemented solutions and the delivered ES in step five in relation to the identified needs of ES in step two. The other shows that the data structure and the data collection process should be updated regularly to ensure that they are useful for political visions, environmental goals, and current standards to meet present urban challenges. In addition, data management in spatial planning of blue-green infrastructure should be based on a suitable organisational and technical structure, with the right expert in the right place and with suitable tools and solutions for data management.

Discussion

Measures to decrease flood risk and increase resilience

The study from Augustenborg (**Paper III**) shows that retrofit with blue-green infrastructure can lower the flood risk if it includes space for controlled inundation, like detention ponds and concave green spaces. The sparse data from before the retrofit makes the before/after comparison uncertain if the analysis of flood claim were to stand alone. In this case a coherent comparison by hydraulic modelling of the sewers in Augustenborg before and after retrofit (Haghighatafshar et al. 2018) in combination with the comparison with similar, neighbouring areas (**Paper III**), confirms the findings of the before/after analysis. The results are rather obvious, as extensive spaces in the urban landscape have been made available for water retention through the retrofit. Based on findings in previous studies (Villarreal et al. 2004, Shukri 2010), a reasonable explanation for reduced flood damage in Augustenborg is a reduction in peak flows and total runoff volumes from blue-green structures.

From **Paper II** and **III**, it is shown how the large-scale and small-scale picture interact to form the pre-requisites for an area. Södra Sofielund is severely affected by flooding, which mainly can be explained by one of the main pipelines in the sewer system of Malmö that runs through the area. A small stream ran earlier

through the area. This watercourse is now tunnelled and constitutes a part of the main pipeline. As shown in **Paper II**, areas along the major flow paths are at higher risk of flooding. The distance to the main sewers seems to be more important for flood risk than the topography, while the topography of course governs the placement of the main sewers. Södra Sofielund is more heavily affected by flooding than Norra Sofielund, despite being located on a higher elevation, because of its location along the main sewer with a large catchment upstream. Despite Augustenborg's lower elevation in comparison with for instance Hindby in the west and Almhög in the south, the flood risk is lower here. In this case, the extensive space made for controlled inundation through blue-green infrastructure might be a proper explanation. The disconnection of stormwater from the combined system would however not have been as beneficial, if one of the main sewers were led through the area, like in Södra Sofielund. The area would still have been flooded by stormwater from upstream areas during intense rainfall.

As the hydrological relation between upstream and downstream areas naturally influences flood patterns, the relation should guide the strategic planning of blue-green infrastructure and other flood preventing measures. The pluvial flood management plan of Copenhagen prioritises implementation of flood prevention measures in central areas, because of the high economic values here (KK 2012). While flood risk is higher in areas with combined system, compared with separate system (**Paper II**), and these often are located in the downstream end of the system, close to the city centre where space is limited, it might be more effective to start implementation in upstream areas, as measures in upstream areas affect all downstream areas as well (Haghighatafshar et al. 2018). The question is thus whether measures should be taken where the flood risk is high, or if areas more upstream should be prioritised to ensure reduced flooding also downstream. There is no right answer to this question, as every city and city district is unique, but large-scale implementation of blue-green infrastructure outside the main city centre are generally more easy and less expensive. However, the downstream effects of large-scale implementation have not yet been fully understood. There are a few studies, but they are often based on modelling with vague or symbolic parameterisation of important hydrological features (Stovin et al. 2013, Viavattene & Ellis 2013, Sun et al. 2014) or without any calibration and validation (Siekman & Siekman 2015, Locatelli et al. 2015).

To be able to handle floods, space for controlled flooding is needed in urban areas, i.e. areas that can store or convey water without incurring damage. Liao (2012) calls this floodable land and has developed a method to assess how much floodable land an urban area consists of. The idea is that the amount of floodable land is related to flood risk. *Floodable area (%)* is defined as the sum of *floodable land* divided by *total floodplain area*. The idea seems useful in urban flood risk assessments, but it is so far only developed for floodplains along rivers. The concept would be interest-

ing to develop for pluvial flooding, as this work indicates that the capacity of detention ponds and other floodable areas are of importance for flood risk reduction. It is a rather simple concept, where the research needs lie more in the categorisation of different stormwater control measures and land uses and less in the equation itself.

Sea level rise will lead to permanent flooding of some areas that currently constitutes land and make storm surges more common in the future. In the Netherlands and other places, large-scale concrete structures are used to keep the sea away. Another solution that has been proposed in the discussion on how to handle sea level rise, is giving (back) land to the sea instead of constructing structural defences it (Smits et al. 2006, Mathur & Cunha 2009). This question is not easy, as culturally and economically important buildings have been built on land that would end up under water by such a process. The discussion can be recognised from the hydro-power industry, which has been criticised when new reservoirs have flooded large land areas, including entire villages. But, as the sea level rises globally, the solution must be seen in relation to the other possibility and that is to construct walls against the sea around all populated areas world-wide. Such constructions will be costly to build, lead to high maintenance cost for an unimaginable future, change the coastal ecosystem, and make people disconnected from the sea (Smits et al. 2006). Similarly, construction of a large tunnel to discharge access water to avoid pluvial flooding in northern Copenhagen is proposed as it is regarded impossible to construct a safe overland flow path due to existing buildings. With limited urban space, the land use conflicts are unavoidable, especially when there is a call for more urban green spaces (Ahern 2013, Walsh et al. 2016) and a view that people's everyday relation to water is important for their preparedness when a severe flooding appears (Liao 2012).

One main drawback and challenge with blue-green infrastructure is indeed the need for space. The study from Augustenborg shows, however, that new green spaces are not always needed to implement blue-green infrastructure. Most of the space used for controlled flooding in Augustenborg was there already before the retrofit, as the yards between the buildings have had a concave shape all since the construction in 1948–1950. As the area had a combined system at the time, these spaces were not connected to the drainage system and therefore not available for water retention. In many areas it is possible to integrate the blue-green infrastructure in the current urban landscape. In Copenhagen, implementation in narrow inner yards have been tested with success. Rain gardens along a street can be used instead of road bumps to reduce the speed of cars. A little can be done many places around the city, with a great total effect. According to Villarreal et al. (2004), a 10-year event could probably have been handled with a conventional separation of foul and stormwater sewers in Augustenborg instead of the blue-green infrastructure, but this would have led to extensive earthwork in the area (*ibid.*) and more pressure on downstream sewers.

In the discussion about space requirements, it should be remembered that many landscaping solutions for flood protection are not vegetated. In Augustenborg, a small, low-laying amphitheatre is placed in the middle of the school yard. Stormwater from the nearby roofs are led to this, stored during rainfall and infiltrated. In Roskilde, Denmark, a large skateboard park can store large water volumes during heavy rain. It is also clear from the study in Augustenborg that urban green spaces do not automatically lower flood risk in an area. In Augustenborg the yards were green also before retrofit, as already mentioned, and some basements were flooded despite the extensive blue-green infrastructure. The reason for the basement floods during the extreme 2014 event is probably that the downslopes to basement parking led the surface water directly from the street to the basements. The landscaping around the buildings were not done in a proper way, which is essential to avoid flooding from surface water.

Present flood and stormwater management should be developed from a single-purpose view with a one-point approach to a multi-disciplinary view with a full spectra approach. This means that the whole range, from the everyday system and processes in the city to the functionality during the most extreme events, is incorporated. The whole system can be managed with a holistic approach, including extreme events, instead of focusing separately on the water issue solely when planning water infrastructure. For economical as well as environmental reasons, an integrated approach is needed. New large-scale single-purpose construction projects, such as huge sewerage tunnels in old combined sewerage systems, have been strongly criticised, for example in Philadelphia (Maimone 2008, Vanaskie et al. 2012), London (Stovin et al. 2013), Beijing (Liu & Jensen 2017), and Copenhagen (*ibid.*). Integrated flood management calls for solutions with multiple purposes, which have a valuable function every day, not only once in 50 or 100 years (Fratini et al. 2012).

All projections of future climate and urban development are highly uncertain, meaning that design of flood defence as well as stormwater management must be done with care. The great uncertainties call for other ways to design and different approaches are needed depending on current and future land use. In new developments, other solutions are possible, and also wanted, than in the dense city centre. Pipes generally have a long lifespan (~100 years) and it would be a waste of money to remove something that to a great extent functions well. In many places, especially in areas with combined system, blue-green infrastructure could rather be used as a complement to reduce the load of stormwater, than to totally replace the pipes, while it in new developments are possible to design with blue-green infrastructure from the beginning. Different urban spaces also call for different solutions. Public squares can, and should also, be constructed with other solutions than for instance private gardens or large parking places. As mentioned in the theoretical background, Hallegatte (2009) proposes a number of strategies to cope with large, future uncertainties. It is crucial to define certain standards based on future climate change and urban

development scenarios. All infrastructure design must be based on guidance resting on a foundation of rigid theory and experience.

Stormwater management should be regarded as a continuum from everyday handling of drizzling rain to control during extreme events. Different solutions have advantages for different situations and therefore a combination of solutions is preferred (Qin et al. 2013). For reduced peaks during most rainfall events, solutions that are good in evapotranspiration and infiltration, like green roofs (Bengtsson 2005), rain gardens and pervious pavements (Pratt et al. 1989, Støvring et al. 2018) are useful. What matters most during extreme events is large storage volumes, preferably spread many places in the urban landscape, in both large and small ponds, rain gardens, wetlands, detention basins. It is sometimes claimed that detention in rain gardens, swales and ponds might be ineffective during heavy rainfall if preceding rainfall have used most of the storage capacity already. However, in southern Sweden, most extreme events happen during the warm summer months (July–August) (**Paper II**) when the weather often is sunny and dry. The flood event on 5 July 2007 is an exception to this.

Durations of one hour or one day is often used for flood hazard modelling and other research studies without any further considerations (Little et al. 2008, Torgersen et al. 2015). During the study of flood characteristics and mechanisms (**Paper II**), analyses of the data material indicated that sub-daily rainfall durations might be critical for flooding in Malmö. This relationship is worth spending more time on to investigate, as the rainfall patterns have implications for design standards and flood prevention.

While riverine flooding is projected to decrease in southern Sweden with climate change due to less snow accumulation during winter months (Rojas et al. 2012), pluvial and coastal flooding are projected to increase due to increased extreme rainfall during summer months (Ohlsson et al. 2009) and rising sea level (Gräwe & Burchard 2012) respectively. National authorities in Sweden, like the Swedish Civil Contingencies Agency (MSB), mainly focus on riverine and coastal flooding, but with climate change, more efforts must be put into pluvial flood risk management. The combined risks are not yet fully understood, but it seems unlikely that extreme rainfall and extreme storm surge should coincide in Sweden, due to their different meteorological forcing.

This work mainly focuses on the hydrology and related solutions to reduce flood risk, and less on the management when flood events happen. It is however inevitable that unexpected things happen, despite proper landscaping, extensive detention of surface water and other flood risk reducing measures. No system is perfect and the work with risk and resilience must therefore reach further and incorporate work with awareness, warning systems, reduced vulnerability, and other non-hydrological measures, as discussed in **Paper I**.

In order to mitigate climate change, reduction of greenhouse gas emission by human lifestyle changes is essential. In parallel, individual households, cities and countries can reduce their climate change impacts by adapting to the projected future climate of their region.

Results from **Paper II** in combination with recent studies on runoff from permeable surfaces (Sjöman & Gill 2014, Berggren et al. 2013) indicate that urban hydrology is largely three dimensional, including not only the areal extent of urban surfaces, but also the features of subsurface soils. While surface runoff is the governing hydrological process for urban flooding, the study from Malmö (**Paper II**) shows that soil saturation through long-lasting rainfall also impacts flood extent on some occasions, i.e. when a heavy rainfall comes after prior long-lasting rainfall. The permeability of urban surfaces and their underlying soil layers differ even at very local scale and long-term processes change the infiltration rate. More precise definitions of urban surfaces are therefore important to better model hydrological processes in urban areas and it is a priority to develop methods for upscaling of small-scale results to city-scale hydrological behaviour (Redfern et al. 2016).

Despite that pollution from storm sewers have been discussed at least since the 1950s, the problem is far from solved. Extensive use of blue-green infrastructure is expected to improve water quality from surface water, but all pollutants are not possible to treat in this way. Like surface runoff should be controlled near the source, also water quality must be handled near the source (Heaney & Sullivan 1971). It is even better if the source could be totally eliminated, but unfortunately heavy metals like copper and zinc remain popular building materials. One way forward could be to require local treatment of runoff from properties where such materials are used, following the polluter pays principle.

Transition towards increased resilience

Transition to a more wide-spread use of blue-green infrastructure is slow. While it already in the late 1990s was generally accepted that stormwater should be attenuated locally (Niemczynowicz 1999), most blue-green infrastructure is still constructed as pilot projects and regarded as tests (**Paper IV**). For transition to take place, changes on different levels are needed. In a transition context it is often pointed out that innovations are essential for inducing change. It is argued that through such an innovation, new social norms are developed concerning how to solve a problem (van der Brugge et al. 2005, de Haan & Rotmans 2011, Ashley et al. 2011, Farrelly & Brown 2011). According to this interpretation of change, a strong focus has so far been put on promoting different types of technical innova-

tions through the channelling of project money to the niche level. This view on transition is however built on a rather simplified view of the interaction between societal actors and legal structure. In the transition literature, there are also voices arguing for the importance of influencing other factors at the landscape level (Koppenjan et al. 2012, Geels 2011, Widarsson 2007, Mguni et al. 2015, Brown & Keath 2008), where for instance Brown & Keath (2008) have argued that drivers at the landscape level are required to stimulate a change in the regime, despite the innovations and new technical solutions at niche level. Yet others have argued that to achieve a transition, changes must occur and be integrated between the levels (Geels and Schot 2007). The results in this work (**Paper IV**), indicates that change is promoted by a combination of alternation at different level of the system. Blue-green pilot projects in the case municipalities do not seem to be transformed into mainstream solutions until proper regulations are in place and the municipal organisation is updated to support such an application. In **Paper IV**, several legal changes in Sweden are suggested, like to re-introduce special, technical requirements, to introduce requirements of site improvement permits when private actors change the infiltration capacity of their land, to introduce a system with permits for stormwater discharge into recipient, and to start to more directly use the EU Water Framework Directive and the EU Floods Directive in urban planning. Other suggested changes are related to the economic barriers found in **Paper IV**, like to differentiate the water fee paid to the municipalities/water utility companies so that property owners with less impervious surfaces pay less, and to allocate money for municipalities to strengthen the urban landscapes capacity to store water. To reduce the uncertainty related to construction and maintenance of blue-green infrastructure, it is important to monitor and evaluate constructed solutions systematically (**Paper IV** and **V**). From **Paper IV** it is also clear that new solutions should be financed by the regular system, rather than by pilot project money, to ensure that experience from the implemented solutions are spread. It is therefore important that the regular departments allocate money for implementation of blue-green infrastructure.

The general knowledge about blue-green infrastructure is good (Ashley et al. 2011), while knowledge about design, construction and maintenance of the solutions is more limited. To ensure that what is learnt from these projects and incorporate it into municipal everyday practices, stronger structures for organisational learning and knowledge transfer are needed. The data generated by such pilot projects must be collected and transformed so that the lessons learnt can be used in future spatial planning of blue-green infrastructure (**Paper V**). The work with GIS in urban planning must be done in a way that facilitates cooperation between different departments and stakeholders, so that a knowledge transfer can take place. To ensure that all planners, engineers, designers, landscape architects, and others involved in the planning and design of blue-green infrastructure have access to sufficient data, a common platform for data management, for instance a spatial data infrastructure

(SDI) with various writing and reading permissions for different users are recommended. Cooperation through a common platform can also help to facilitate better cooperation to overcome ‘silo’ thinking in the planning of blue-green infrastructure. Besides better structures for cooperation, the results from **Paper V** shows that better data in general is needed, especially data on the qualities of the existing blue-green infrastructure and data and analyses of where to implement the solutions are missing. As a next step, the framework developed in **Paper V** should be tested together with municipal and water utility officials to clarify where and how data is collected and used in the strategic and detailed planning of blue-green infrastructure and how this process could be improved.

While interdisciplinary cooperation and understanding are crucial in the work with blue-green infrastructure, specialists still are necessary. Complex solutions require deep understanding, which can only be achieved by specialists. But specialists need a general understanding of the other disciplines and someone, who preferably is an generalist, must coordinate the work to make sure that knowledge from all disciplines are considered. The work with blue-green infrastructure thus calls for collaborative work in groups with both specialist and generalist knowledge. While stormwater engineers tend to focus solely on the hydrological perspective of urban green spaces, manifested as infiltration, evapotranspiration, and detention (Stahre 2008), ecologists tend to focus solely on the ecological perspective of them, e.g. tree planting, fruits, composting, and nectar provision (Gaston et al. 2013). If blue-green infrastructures shall provide multiple functions (Turner 1995), the different objectives must be combined (Turner 1995). As shown in **Paper III**, green areas do not provide flood protection only by their existence. The hydrological quality of them are important for their function during extreme precipitation. Similarly, the ecological quality of for instance a detention pond is important for its ecological functionality. In addition to hydrological and ecological functions, blue-green infrastructure should provide other qualities for the urban landscape, like aesthetical, technical and cultural qualities.

Conclusions

Stormwater management has gone from a single-disciplinary field to involve actors from several disciplines, like hydrology, urban planning and design, biology, and risk management. This thesis has given a hydrological perspective of urban, pluvial flooding, where the spatial distribution of flooding and its relation to drainage system, blue-green infrastructure, flow paths, rainfall patterns, and sea level has been analysed. It was found that flooding during intense rainfall often is located closely to the main overland flow paths and the main sewers, while flooding during rainfall with longer duration seem to be more randomly distributed. It can also be concluded that combined sewers are more affected by flooding than separate sewers and that blue-green infrastructure can reduce urban, pluvial flooding.

Socio-technological transition has also been studied. Such transition is complex, and it was found that a combination of a bottom-up approach, where innovation is used to produce more knowledge about design, construction, function and maintenance of blue-green infrastructure, and a top-down approach, where legal and organisational changes are made to enforce long-term changes in the stormwater management system, is needed. A total regime shift is neither expected nor desired—a slow transition to a regime where a combination of pipe-bound and blue-green drainage is used is more likely.

To make advances in the use of urban blue-green infrastructure with more and better green spaces, including better management of urban flooding, spatial data must be organised in a more useful way. A framework was developed that can be used to discuss proper data collection and management for spatial planning of blue-green infrastructure in urban areas.

The studies have focused on Malmö, Sweden, including the retrofitted area of Augustenborg as well as some neighbouring cities in Scania. In cities with similar climatic and socio-technical circumstances similar patterns are likely to be found, while the validity in other contexts must be verified.

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