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PhD Thesis
June 2019

DTU Environment
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While the manifold projects of capital, empire, and science are busy making Nature with a capital ‘N’ – external, controllable, reducible – the web of life is busy shuffling about the biological and geological conditions of capitalism’s process. The “web of life” is nature as a whole: nature with an emphatically lowercase n. This is nature as us, as inside us, as around us. It is nature as a flow of flows. Put simply, humans make environments and environments make humans – and human organization.

Jason W. Moore,

Capitalism in the Web of Life, 2015

Preface

The work presented in this PhD thesis was conducted at the Department of Environmental Engineering of the Technical University of Denmark (DTU) under the supervision of Professor Peter Steen Mikkelsen, with Professor Karsten Arnbjerg-Nielsen as co-supervisor. The work was conducted between November 2012 and April 2019 (as a part-time position, interrupted by parental leaves in 2013-2014 and 2016-2018). The PhD project was funded by a grant from the Foundation for Development of Technology in the Danish Water Sector (grant number 7255-2011) and by DTU.

The thesis is organized in two parts: the first part is a synopsis, and the second part consists of the papers listed below, which will be referred to in the text by their paper number written with the Roman numerals **I-V**:

I **Lerer, S.M.**, Arnbjerg-Nielsen, K., Mikkelsen, P.S., 2015. A Mapping of Tools for Informing Water Sensitive Urban Design Planning Decisions—Questions, Aspects and Context Sensitivity. Water, Vol. 7, 993-1012, DOI:10.3390/w7030993

II Sørup, H.J.D, **Lerer, S.M.**, Arnbjerg-Nielsen, K., Mikkelsen, P.S., Rygaard, M., 2016. Efficiency of stormwater control measures for combined sewer retrofitting under varying rain conditions: Quantifying the Three Points Approach (3PA). Environmental Science & Policy, Vol. 63, p. 19-26, DOI: 10.1016/j.envsci.2016.05.010

III Andersen, J.S., **Lerer, S.M.**, Backhaus, A., Jensen, M.B., Sørup, H.J.D., 2017. Characteristic Rain Events: A Methodology for Improving the Amenity Value of Stormwater Control Measures. Sustainability, Vol. 9, No. 10, 1793, DOI:10.3390/su9101793

IV **Lerer, S.M.**, Righetti, F., Rozario, T., Mikkelsen, P.S., 2017. Integrated hydrological model-based assessment of stormwater management scenarios in Copenhagen's first climate resilient neighbourhood using the three point approach. Water, Vol. 9, No. 11, 883, DOI:10.3390/w9110883

V **Lerer, S.M.**, Sørup, H.J.D, Arnbjerg-Nielsen, K., Mikkelsen, P.S., draft manuscript. SCM-potential: a quantitative digital tool for early stage design of green stormwater infrastructure.

In addition, the following publications, not included in this thesis, were concluded during this PhD study:

Conference proceedings:

Jensen, D.M.R., **Lerer, S.M.**, Vezzaro, L., Sørup, H.J.D., Arnbjerg-Nielsen, K., Li, X., Mikkelsen, P.S., 2018. Early stage planning tools for stormwater quantity and quality management in Denmark and China. In: Mannina, G. (Ed.), Proc. 11th Int. Conf. on Urban Drainage Modelling, Palermo, Italy, 23-26 September, pp. 1097-1100.

Sørup, H.J.D., Brudler, S., Godskesen, B., Dong, Y., Rygaard, M., **Lerer, S.M.**, Arnbjerg-Nielsen, K., 2017. Essential Societal Service Functions and Planetary Boundaries: The Case of Sustainable Urban Water Management. Abstract from ISIE 2017: Science for Sustainable and Resilient Communities, Chicago, United States. 1 pp.

Lerer, S.M., Madsen, H.M., Smit Andersen, J., Rasmussen, H., Sørup, H.J.D., Arnbjerg-Nielsen, K. & Mikkelsen, P. S., 2016. Applying the "WSUD potential"-tool in the framework of the Copenhagen Climate Adaptation and Cloudburst Management Plans. Proc. of 9th Int. Conf. on Planning and Technologies for Sustainable Urban Water Management - NOVATECH. Lyon, France, 4 pp.

Lerer, S.M., Sørup, H.J.D., Arnbjerg-Nielsen, K., Mikkelsen, P.S., 2016. A new tool for quantifying the hydrological effects of LID retrofit designs – the power of simplicity. 2016 International Low Impact Development Conference, Beijing, China, 26-29 June. Paper ID 479, 7 pp.

Smit Andersen, J., **Lerer, S.M.**, Sørup, H.J.D., Backhaus, A., Jensen, M.B., 2016. Characteristic Rain Events – A tool to enhance amenity values in SUDS-design. Proceedings of 9th International Conference on Planning and Technologies for Sustainable Urban Water Management - NOVATECH. Lyon, France, 4 pp.

Sørup, H.J.D., Brudler, S., **Lerer, S.M.**, Miraglia, S., Georgiadis, S., Arnbjerg-Nielsen, K., 2016. What does it take to practice sustainable flood risk management?. Abstract from Sustain-ATV Conference 2016, Kgs. Lyngby, Denmark.1 p.

Sørup, H.J.D., Brudler, S., **Lerer, S.M.**, Miraglia, S., Georgiadis, S., Dong, Y., Arnbjerg-Nielsen, K., 2016. Sustainable flood risk management – What is sustainable?. Proc. 9th Int. Conf. on Planning and Technologies for Sustainable Urban Water Management - NOVATECH. Lyon, France, 4 pp.

Lerer, S.M., Sørup, H.J.D., Arnbjerg-Nielsen, K., Mikkelsen, P.S., 2015. LAR-potential: a new planning tool to support sustainable stormwater management. Book of Abstracts. DTU's Sustain Conference, Technical University of Denmark (DTU).

Lerer, S.M., Sørup, H.J.D., Arnbjerg-Nielsen, K., Mikkelsen, P.S., 2015. A new tool for quantifying the impacts of water sensitive urban design – the power of simplicity. In: Maere, T., Tik, S., Duchesne, S., Vanrolleghem, P.A. (Eds), Proc. 10th Int. Conf. on Urban Drainage Modelling, Quebec, Canada, pp. 285-289.

Lerer, S.M., Sørup, H.J.D., Arnbjerg-Nielsen, K., Mikkelsen, P.S., 2015. Quantification the Effects of Water Sensitive Urban Design in a Simplifying Manner. Poster presented at European Climate Change Adaptation Conference 2015, Copenhagen, Denmark. 1 p.

Sørup, H.J.D., **Lerer, S.M.**, Arnbjerg-Nielsen, K., Mikkelsen, P.S., 2015. Quantitative potential for stormwater control measures. Book of Abstracts. DTU's Sustain Conference. Technical University of Denmark (DTU).

Danish language publications:

Lerer, S. M., Vester, M. A., Sørup, H. J. D., Arnbjerg-Nielsen, K. & Mikkelsen, P. S., 2015. Værktøj til vurdering af LAR-potentiale. Vand & Jord, vol 22, no. 4, pp. 127-130.

Lerer, S. M., & Mikkelsen, P. S., 2015. Kvantitativt potentiale for håndtering af regnvand – afrapportering for projekt støttet af VTU-Fonden. Vandsektorens Teknologiudviklingsfond.

Lerer, S. M.; Sørup, H. J. D., 2015. Oversvømmelser - Byens ekstremregn. Dansk Byplan.

Lerer, S. M.; Sørup, H. J. D., 2016. Lokal afledning af regnvand - Byens hverdagsregn. Dansk Byplan.

In this online version of the thesis, papers **I-V** are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from DTU Environment, Technical University of Denmark, Miljoevej, Building 113, 2800 Kgs. Lyngby, Denmark, info@env.dtu.dk.

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I’d like to thank the Foundation for Development of Technology in the Danish Water Sector as well as the project group members from Aarhus Vand and HOFOR for their contributions and support during the first part of the PhD project.

My main supervisor has played a central role in making all this happen – from writing the original research proposal through encouraging me to seek the position to showing understanding and support through the hard times we had with our first borne. I truly appreciate your empathy, your inspiration-based leadership, and all the trust and freedom that I have been given.

Thanks to my co-supervisors, official as well as “adopted”, and all the people I have had the pleasure to work closely with, for all your inputs, contributions, shared insights, feedback, opinions and advice.

I have had the honour and pleasure of co-supervising many talented students through their bachelor and master theses: thank you for all that you have taught me.

I have also had many changing colleagues and office mates through the years at DTU – thanks to all of you for the good talks and for remembering to take me along for lunch and reminding me to take a walk and get some fresh air sometimes ☺

I’d like to take this opportunity to also thank the good people I have worked with since embarking on my engineering studies at DTU and through my years at DHI and HOFOR – I consider our shared experiences and the knowledge you have shared with me as formative to my professional development and understanding of the world, bits of which I tried to crystalize in this thesis.

Last but not least I must thank my family for making me who I am, and for tolerating me also when I had had a hard day in the office… You make my life meaningful. I love you deeply.

Summary

Stormwater sewers are one of several essential infrastructure systems that enable life in modern cities. In recent years, a combination of increased urbanization and changes in precipitation patterns has challenged the capacity of existing sewer systems, and is expected to increasingly do so in the future. Nature based stormwater control measures (SCMs) have shown potential to help meet these challenges while also improving the sustainability of the stormwater system and liveability in the city.

The Three Point Approach (3PA) has proven a useful tool for improving communication among the different types of professionals who plan and design SCMs. It defines three distinct domains of stormwater management: domain A is the domain of “day-to-day values”, domain B is the domain of “technical optimization”, and domain C is the domain of “extreme events”. The bottom line message of the 3PA is that it is important to address all three domains whenever new projects are considered. Unfortunately, this is rarely done in practice, and especially domain A seems to be neglected.

The overall objective of this PhD project was to develop tools to assist different professionals in planning and designing nature based SCMs. The tools were to be simple and easy to use, provide essential quantitative information about the impact of SCMs on a site’s hydrology, and build upon the proven communication capabilities of the 3PA. To this end, we investigated which tools are already available and how useful they are; we explored ways to “operationalize” the 3PA; and we developed methods for condensing the most essential information from complex hydrological models to tangible, intuitively logical indicators.

Our literature review of existing tools showed that there is a myriad of tools. We proposed categorizing them according to what type of questions they could assist in answering: “how much” (water, pollution, etc. can be managed via SCMs), “where” (to situate SCMs) and “which” (SCM is the best); or any combination hereof. Other variations among the tools include what degree of complexity they include in their processing, what degree of expertise they require from the user, what type of professional background of the user they are designed for, whether they are most useful for making overall planning strategies or for designing specific solutions, and much more. We concluded that although there are many tools out there already, the variability in the demands that shape them also entails that there is ample room for more tools.

The first tool we developed was a quantitative version of the 3PA. We defined a return period for each domain, and through analysis of historical rainfall records calculated a rainfall depth that can be considered representative for the upper boundary of each domain. We also added a second vertical axis that notes each domain's share of the annual rainfall. This shows that in Denmark, although the upper boundary of domain A is only 20 mm, the domain includes 75% of the annual rainfall, which illustrates the large potential that lies in this domain.

The second tool, the Characteristic Rain Events (CREs), was developed specifically to draw attention to the aesthetic performance of SCMs during times where there is only little water in them, i.e. in domain A (which is the bulk of the time). The CREs were carefully chosen among historical rain events to give designers tangible manifestations of frequent rains. These can be used to assess how much rainwater becomes visible in an SCM under frequent events, thus improving the day-to-day aesthetic value of the SCM.

For situations where strategic planning requires thorough understanding of possible retrofit options' impact on complex stormwater systems, we demonstrated how the 3PA can be used to structure state-of-the-art distributed modelling studies and their output. Our method includes running long term simulations for quantifying water balance impacts as an indicator for performance in domain A, and presenting this alongside single quantitative indicators for domain B (sewer surcharge) and C (surface flooding), calculated from results of traditional short term simulations using the design storm approach. Results of using this method on a case study show that this may highlight sustainability gains that would otherwise be ignored.

The third tool, SCM-potential, suggests a new method for quickly calculating SCM impact on two key hydrological indicators, designed to give professionals interactive feedback on their site design choices. Here we used the 3PA as a visual framing of the first key indicator, which shows the return period of overflow from the site. The second key indicator shows how the design will impact the annual water balance of the site. Both indicators are quickly returned by the tool thanks to tabulated values of key results from long term hydrological simulation of SCMs. In this manner we make essential hydrological information more easily accessible to professionals in situations where time or resources do not allow for setting up complex hydrological models, such as the early stages of a design process.

Dansk sammenfatning

Afløbssystemer er en nødvendig infrastruktur for at understøtte livet i moderne byer. Klimaændringer og tiltagende urbanisering har i de senere år imidlertid øget presset på afløbssystemerne, og det forventes at dette pres vil stige yderligere fremover. Naturbaserede teknologier til lokal håndtering af regnvand (LAR-elementer) har vist potentiale til at bidrage til at løse disse udfordringer, samtidig med at de kan bidrage til at øge systemernes bæredygtighed og livskvaliteten i byerne.

Trepunktsmetoden er en simpel kvalitativ model der kan forbedre kommunikationen mellem forskellige fagpersoner der arbejder med LAR-løsninger. Trepunktsmetoden definerer tre domæner for beslutninger relateret til regnvandshåndtering: domæne A domineres af dagligdags værdier, domæne B handler om optimering af afløbssystemer, og domæne C er de ekstreme hændelsers domæne (dvs. oversvømmelse). Kernebudskabet i trepunktsmetoden er, at et succesfuldt klimatilpasningsprojekt må forholde sig til alle tre domæner. Desværre sker dette ofte ikke i praksis, og især domæne A bliver ofte overset.

Formålet med dette PhD-projekt var at udvikle værktøjer, der kan hjælpe forskellige fagpersoner med at planlægge og designe LAR-løsninger. Værktøjerne skulle være simple og nemme at bruge, levere en kvantitativ vurdering af LAR-løsningers effekt på områdets vandstrømme, og bygge videre på trepunktsmetodens succesfulde kommunkationstilgang. Med dette formål for øje blev det undersøgt, hvilke værktøjer der findes allerede og hvor brugbare de er; det blev undersøgt hvordan trepunktmetoden kan ”operationaliseres” på en måde så alle tre domæner kommer i spil ved planlægning og dimensionering af LAR, herunder særligt domæne A; og der blev udviklet metoder til at kondensere den vigtigste information fra komplekse hydrologiske modeller til håndgribelige, intuitivt forståelige indikatorer.

Gennemgang af den videnskabelige litteratur viste, at der findes rigtig mange værktøjer allerede. De blev kategoriseret i forhold til, hvilke typer spørgsmål de kan hjælpe med at besvare: ”hvor meget” (vand, forurening osv. kan en LAR-løsning håndtere?), ”hvor” (er det bedst at placere et LAR-element?), ”hvilket” (LAR-element er bedst?), eller enhver kombination heraf. Andre forskelle mellem værktøjerne handlede om, hvor meget kompleksitet de medtager i deres analyser, hvor stor en ekspertise de kræver af brugeren, hvilken faglig baggrund brugeren forventes at have, hvorvidt de er egnet til at under-

støtte overordnet planlægning eller konkrete designløsninger, og meget mere. Det blev konkluderet, at selv om der allerede findes mange værktøjer, så betyder den store variation i de krav der har dannet baggrund for værktøjerne, at der behov for og rum til flere værktøjer.

Det første værktøj udviklet i projektet var en kvantitativ version af trepunktsmetoden. En konkret gentagelsesperiode blev defineret for hvert domæne, og via analyse af historiske regntidsserier blev en regndybde beregnet, der kan anses for at repræsentere hvert domænes øvre grænse. Derudover blev en sekundær vertikal akse tilføjet, der viser hvert domænes andel af den årlige nedbør. Resultaterne viste, at selvom den største regn i domæne A kun indeholder 20 mm, så udgør de regnhændelser der falder indenfor domæne A tilsammen 75 % af den årlige nedbør, hvilket fremhæver det store potentiale der ligger i domænet ud fra f.eks. et vandressourceperspektiv.

Det næste værktøj, Karakteristiske Regnhændelser, blev udviklet til at understøtte design af LAR-løsninger med fokus på, hvor godt de fremviser regnvandet i dagligdags situationer, dvs. i domæne A (som udgør det meste af tiden). De karakteristiske regnhændelser blev omhyggeligt udvalgt blandt historiske regnhændelser for at give et håndgribeligt udtryk for, hvordan ”dagligdags regn” kan manifestere sig på forskellige måder. De kan bruges til at udforme en LAR-løsning, så den ikke blot er stor nok til at håndtere den regnmængde den dimensioneres efter, men også bidrager med smukt synligt vand efter små og mere hyppige regnhændelser.

I nogle planlægningssituationer kan der være behov for at få en grundig forståelse af, hvordan forskellige klimatilpasningsløsninger vil påvirke det samlede afløbssystem. Det blev vist, hvordan man kan strukturere et omfattende modelleringsstudie og præsentere resultaterne i henhold til trepunktstilgangen. Den udviklede metode indbefatter at køre langtidssimuleringer og bruge resultaterne herfra til at udregne en årlig vandbalance som indikator for systemets præstation i domæne A og præsentere denne sammen med en indikator for funktionen i domæne B (andel af brønde i afløbssystemet, der løber over) og en indikator for funktionen i domæne C (oversvømmelse på terræn). Resultater fra et casestudie i København (Skt. Kjelds kvarter) viste, at metoden kan synliggøre bæredygtighedsaspekter ved de forskellige scenarier, som normalt ville blive overset.

Det tredje og sidste værktøj udviklet, LAR-potentiale, demonstrerer hvordan man kan give et hurtigt overslag på en LAR-løsnings effekt. Her bruges trepunktsmetoden som en grafisk referenceramme for den ene indikator, gentagelsesperioden for overløb fra LAR-løsningen, og den anden indikator viser hvordan LAR-løsningen påvirker stedets årlige vandbalance. Begge indikatorer returneres øjeblikkeligt ved hjælp af tabulerede hovedresultater fra langtidssimuleringer af udvalgte LAR-elementer. På denne måde gøres essentiel hydrologisk viden mere tilgængelig i situationer, hvor tid og ressourcer ikke gør det muligt at opstille komplekse modeller, såsom i de tidlige faser i en designproces.

Abbreviations

3PA	Three Point Approach
CRE	Characteristic Rain Events
CSO	Combined Sewer Overflow
ET	Evapotranspiration
GI	Green Infrastructure
GSI	Green Stormwater Infrastructure
LAR	Lokal Afledning af Regnvand
LCA	Life Cycle Analysis
LID	Low Impact Development
MU	MIKE URBAN
NBS	Nature Based Solutions
SCM	Stormwater Control Measure
SUDS	Sustainable Urban Drainage System
SWMM	StormWater Management Model
WSUD	Water Sensitive Urban Design
WWTP	WasteWater Treatment Plant

Table of contents

1 Introduction

1.1 Motivation

Stormwater sewers are one of several essential infrastructure systems that enable life in modern cities. In recent years, a combination of increased urbanization and changes in precipitation patterns has challenged the capacity of existing sewer systems, and is expected to increasingly do so in the future. At the same time, city dwellers have increased expectations towards liveability in their cities and sustainability of the systems that support it, which also presents new challenges to stormwater management. One type of solutions which has shown a potential to respond to these challenges is Green Stormwater Infrastructure (GSI), also known as Low Impact Development (LID, mainly in the US), Sustainable Urban Drainage Systems (SUDS, mainly in the UK) (Fletcher et al., 2015), Nature Based Solutions (NBS, in the EU) and Sponge Cities (in China). The single elements of GSI can be referred to as Stormwater Control Measures (SCMs). Examples of nature based SCMs include rain gardens, bioretention units, green roofs, soakaways, and detention ponds.

Nature based SCMs are fundamentally different from traditional pipe-based sewer systems in several ways, including the processes they employ, the materials used, and the space they occupy. These differences necessitate new approaches to the planning, design, construction and maintenance of SCMs and sewer systems that include them. The fact that SCMs are generally placed above ground is especially challenging during the planning and design stages, because it entails that stormwater engineers, who are used to design systems below ground, now need to interact with other professionals who are responsible for forming the urban space. Above-ground SCMs need to compete for space, which is a limited resource in cities, and hence they need to deliver other benefits than stormwater management to justify their space uptake – they must be “multifunctional”.

The Three Point Approach (3PA) has proven a useful tool to improve the communication between engineers, urban designers and other stakeholders in the process of planning above-ground SCMs (Fratini et al., 2012). It is a graphical qualitative simplification of the complex processes that govern urban stormwater dynamics. It defines three distinct domains of operation: domain A is the domain of “day-to-day values”, domain B is the domain of “technical optimization”, and domain C is the domain of “extreme events”.

The bottom line message of the approach is that it is important to address all three domains whenever new projects are considered. This requires collaboration between professionals with different backgrounds. Unfortunately, this is rarely done in practice, and especially domain A seems to be neglected (Madsen et al., 2018).

There are numerous barriers to the uptake of SCMs in practice, including institutional, legislative and economic barriers, as documented by numerous studies (e.g. Brown and Farrelly, 2009; Cettner et al., 2014; Dhakal and Chevalier, 2017; Kim et al., 2017; Roy et al., 2008; Wihlborg et al., 2019; Yang et al., 2018). Many studies report a need for more knowledge and guidelines, and some studies mention specifically a lack of appropriate decision support tools, especially tools that are easy to use (Ahammed, 2017; Ahiablame et al., 2012; Dietz, 2007; Eckart et al., 2017). The need for a tool to support planning of SCMs in Denmark was concretized in collaboration between DTU Environment and the utility companies of Copenhagen and Aarhus and led to the establishment of this PhD-project.

1.2 Research Objectives

In light of the above, the overall objective of this PhD project was to develop tools to assist different professionals in planning and designing nature based SCMs. The tools were to be simple and easy to use, provide essential quantitative information about the impact of SCMs on a site’s hydrology, and build upon the proven communication capabilities of the 3PA.

To support this objective, the following research questions were formulated:

1. Which tools are already available and how useful are they for different professionals?
2. How can we “operationalize” the 3PA so that we keep professionals attentive to all three domains throughout their plans and designs?
3. Specifically, how can we help professionals improve their plans and designs with regards to domain A of the 3PA?
4. How can we develop tools that are simple and easy to use while respecting the complexity of urban hydrological processes?

The answer to the first question is presented in Section 3 (Existing tools and methods). The tools we developed, which suggest different ways of addressing the following questions (2-4), are presented in Section 4 (Tools and methods developed). Section 5 discusses some cross-cutting methodological issues, while Section 6 (Conclusions) summarizes the findings, addressing all four research questions, and Section 7 provides some perspectives on future research directions.

For an overview of how the papers (in the second part of the thesis) respond to the research questions, please see **Table 1** below.

Table 1: Research questions and which papers address them.

Research Questions \ Papers	I	II	III	IV	V
1. Which tools are available	X				
2. Operationalize 3PA		X		X	X
3. Draw attention to domain A			X	X	X
4. Develop simple tools		X	X		X

2 Theoretical Background

2.1 Stormwater management today

Brief history of modern stormwater systems

Water is a prerequisite for life, and well-functioning water infrastructure is a prerequisite for human settlements. There are two main man-made flows of water in and out of a modern city: tap water (not always suitable for drinking but often used for washing, cleaning and flushing toilets) and wastewater (the dirty water that results from using the tap water). In addition to these manmade flows there is usually another significant natural flow in and out: rain that falls directly on the surface of the city, of which some portion, depending on the quantity and intensity of the rain and on the properties of the different surfaces in the city, will start flowing on the surfaces, and this is what we call stormwater, or urban runoff.

Stormwater has always posed a challenge for human settlements, but the larger and denser they grow, the more necessary it becomes to “do something about it”. Therefore gutters are a feature seen in almost all cities, also pre-modern cities. These gutters were often also used to discard of household wastes, including faeces. During the industrial revolution, where many European cities began growing very rapidly, the pollution caused by such practices became unbearable. It was not yet fully established that contact with faeces was a source of disease spreading, although there were several studies indicating this, but the stench alone was enough of a driver to start constructing the first underground pipes for drainage purposes, called sewers.

Following the lead of cities such as London, Hamburg and Paris, by the late 1800’s many European cities had constructed underground sewer systems, including Copenhagen (Winther et al., 2011). This often happened in conjunction with the establishment of piped drinking water systems. Historical evidence shows that it was suggested, in Copenhagen and other places, to construct a double system of sewers – one for stormwater and one for wastewater – but the increased complexity and costs of such a separate system were the reasons that most cities chose to construct a combined sewer system (Cettner et al., 2012; Winther et al., 2011). Separate sewers generally emerged later, in Denmark mainly during the second half of the 1900’s. However, given that the early sewers were of a very solid quality, and buried underground in now historical and busy city centres, their legacy prevails, and the management of stormwater in many places remains closely linked with the management of wastewater.

Given that combined sewer systems carry both stormwater and wastewater, their construction did not eliminate the problem of pollution but only moved it from inside the cities to the natural water bodies around them where sewers had their outlets (river, lakes, estuaries, etc.). Soon this problem became too big to ignore, and the sewer systems were extended with two new parts: interceptor lines and wastewater treatment plants (WWTPs). In combination, and with gradually increasing cleansing efficiency at the treatment plants, the emissions from combined sewers were substantially reduced, though one "joker" keeps acting up: the stochastic nature of rainfall. Any reasonable dimension of sewers and treatment plants is bound to be periodically exceeded by stormwater inflow, which results in overflows at the former outlet locations (known as CSO, combined sewers overflow) and at the WWTPs (known as by-pass). On national level these point emissions constitute a small fraction of the total emissions of key nutrients like nitrogen and phosphorus (Brudler et al., 2019; Thodsen et al., 2018), but on local level they can be critical for achieving high-quality in-city or near-city recreational waters, such as the harbour baths that have helped the city of Copenhagen gain reputation as one of the most liveable city in the world (Mercer, 2019).

Separate sewer systems gained popularity during the 20th century and largely became standard in "the new world", as well as in new urban developments in Europe mainly from the 1960's and onwards (Winther et al., 2011). For many years the separate runoff was considered clean enough to be discharged directly to the environment, and did not have any apparent impact on the receiving waters. However, as other pollution sources were reduced, and society's understanding of invisible pollutants increased, attention was directed to the composition of stormwater, and significant pollutants were found in it, including nutrients, heavy metals and many different xenobiotics (Eriksson et al., 2005). Furthermore, an impact on the flow regime of rivers was noted in those cases where the city lies within the catchment of a river: as the city grows and a larger amount of surface is sealed (i.e. is covered with houses and paving materials), less water infiltrates to the ground (where it can contribute to baseflow to the river) and more water is discharged to the river as short and intense flows, causing periodical dry outs, erosion of the river bed, etc. (Anim et al., 2019). A commonly applied control measure is a detention basin, which reduces both the hydraulic and pollutant load to the receiving waters, yet does not usually improve baseflow.

Current trends affecting stormwater systems

The term “The Anthropocene”, first proposed by Crutzen and Stoermer in 2000, signifies that we live in an age where human activities have impacted the entire planet to a degree that its current state is functionally and stratigraphically distinct from the Holocene (Waters et al., 2016). One category of impact is climate change, where manmade emissions of “greenhouse gases” have caused a trend of global warming that is well evident already today and is projected to continue in the future (Masson-Delmotte et al., 2018). Warming of the planet induces i.a. changes in rainfall patterns and rise of sea levels, both of which negatively impact the ability of existing stormwater systems to effectively drain cities: more intense rainfall events, as already observed in Denmark and projected to increase in the future (Gregersen et al., 2014), entail more frequent exceedance of sewer capacity; higher sea levels, projected to impact sea surge levels in Denmark significantly in the near future (City of Copenhagen, 2011), entail reduced hydraulic gradients in the sewers, ultimately leading again to more frequent exceedance of sewer capacity. Exceedance of sewer capacity means that stormwater cannot enter the sewers in some parts of the system and/or stormwater surcharges from the sewers to the city surface, in both cases causing local flooding, which, in severe cases, adds up to larger scale flooding.

The start of the Anthropocene, recently suggested in the middle of the 20th century (Waters et al., 2016), coincides with an accelerated growth of urban populations, a trend known as urbanization (Unites Nations, Department of Economics and Social Affairs, 2018). The UN estimates that more than 55 % of the world’s population lives in urban areas today, and projects that by 2050 the urban percentage will be 68 %. Cities grow by expanding their territory and by increasing the density of dwellers. The latter usually entails sealing more land surface in the city and thus increasing the load on existing stormwater systems; the former will usually also increase the load on existing systems (as long as the expansion happens within the same watershed, given that the stormwater mains usually run along the natural drainage paths). The impact of climate change and the impact of urbanization on urban flood risk seem to have a similar level of significance (Kaspersen et al., 2015).

In the face of these and other intensifications of environmental stresses, humans are formulating concepts such as sustainability and liveability. The term sustainability arises from the concept of sustainable development, which was first introduced by the UN in the Brundtland Report in 1987 to describe a development that “meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Comission on Environment and Development, 1987). Sustainability is often considered to have three dimensions: environmental, social and economic, but further interpretation of what sustainability means still displays large variability. In relation to stormwater systems the focus has mainly been on reducing local emissions, i.e. the pollution of receiving waters (e.g. Harremoës, 2002; Niemczynowicz, 1994), in recent years coupled with a focus on reducing global emissions (from construction through operation and maintenance to decommissioning) often addressed using Life Cycle Analysis (LCA) (e.g. Brudler et al., 2016; Byrne et al., 2017). LCA studies usually compare emissions from different scenarios, which can be described as assessing *relative* sustainability. However, in order to truly ensure that we leave a reasonably functioning planet to future generations, it would be more appropriate to look at *absolute* sustainability, as attempted with the Planetary Boundaries approach (Steffen et al., 2015).

The term liveability has a longer history, through which its meaning has shifted considerably (Kaal, 2011); nowadays it is generally understood as “the sum of factors that add up to a community’s quality of life” (Okulicz-Kozaryn and Valente, 2018). Liveability is evaluated using a variety of indicators, which to some degree overlap with the three dimensions of sustainability. I would argue that one major difference between the terms sustainability and liveability lies in their spatial and temporal scope: while sustainability specifically addresses future generations and inevitably considers impacts on the entire planet, liveability focuses on the present and near future (current generations) and limits its analysis to a single city at a time (generally not considering the impacts the city metabolism has outside of the city). In relation to stormwater systems, the focus of the liveability approach is hence on their efficacy at delivering their basic services such as drainage and prevention of flooding, together with their potential for delivering added benefits for city dwellers such as greenery, recreational spaces, etc. (De Haan et al., 2014).

While the ideas of sustainability and liveability have some overlap, they are also in potential conflict: liveability can often be enhanced by using *more* resources, while (absolute) sustainability inevitably requires using *less* resources (given that current civilization is consuming more than its fair share, especially in rich societies such as Denmark (Global Footprint Network, 2018)). The tension between the wish to improve standards of living and the wish to not overspend resources becomes even more evident when looking at the needs of developing countries and their megacities, which has led some researchers to point out the not-so-sustainable aspect of the UN's Sustainable Development Goals (SDGs) and the need to align them with the Planetary Boundaries (PBs), both in general (Randers et al., 2018) and specifically with respect to urban water systems (Sørup et al., n.d.). The solutions to this challenge are not evident, but it seems clear that solutions must be smart (Chocat et al., 2007; Randers et al., 2018), in the sense that they solve multiple challenges synergistically and frugally; in other words, solutions must to be *multifunctional*.

2.2 Nature based stormwater control measures

Fletcher et al. (2015) provide a thorough review of the different "alternative" strategies for managing urban runoff around the world, including Low Impact Development (LID) in the US, Sustainable Urban Drainage Systems (SUDS) in the UK, Water Sensitive Urban Design (WSUD) in Australia, and more. The authors demonstrate that these terms not only use different words but also refer to slightly different visions, influenced by their local contexts. The authors conclude by suggesting the more neutral term Stormwater Control Measures (SCMs). This thesis adopts the term SCM when referring to the individual technologies used for managing stormwater locally. Meanwhile, there is also a need for a term that reflects the vision that mandates the use of SCMs. In this thesis I will use the term Green Stormwater Infrastructure (GSI), for the reasons explained in the following.

Green Infrastructure (GI) is a broad term, with roots in landscape architecture and urban ecology, that promotes networks of green spaces which maximize the provision of ecosystem services such as amenity, human health, microclimate regulation, stormwater management and more (Dover, 2018; Fletcher et al., 2015; Tzoulas et al., 2007). An important principle of GI is multifunctionality (Hansen and Pauleit, 2014; Mattijssen et al., 2017; Wang and Banzhaf, 2018). Examples of the benefits that can be attributed to urban green include reduced mortality and violence and improved emotional well-being and physical activity (Kondo et al., 2018), the latter especially significant for children (Tillmann et al., 2018; Ward et al., 2016) and in low-income neighbourhoods (Brown et al., 2018). It is interesting to note that the mere sight of a tree has some quantifiable positive impacts on humans (Ulrich, 1984), while an active use of the urban green space is required for other impacts such as improved longevity (Takano et al., 2002).

For some time the term GI was used within the stormwater community to express the same kind of approach to stormwater management as conveyed by terms such as LID, SUDS and WSUD (Fletcher et al., 2015). In order to distinguish GI with a focus on stormwater management from the more general concept of GI this text will refer to it as Green Stormwater Infrastructure (GSI). Compared to other popular terms, GSI has:

- A clear emphasis on "green", i.e. vegetated solutions, referring to all the other benefits achievable through greening of cities, and stressing the value of multifunctionality;
- A focus on "stormwater", in contrast to e.g. the term WSUD which encompasses the entire urban water cycle;
- The word "infrastructure" indicates the importance of combining individual solutions into a larger interrelated system that provides vital services in an efficient manner.

GI and GSI are related to another emerging concept that has been strongly promoted by the European Commission: Nature-Based Solutions (NBS) (Lafortezza et al., 2018). Whenever NBS is mentioned in this text it can be assumed to mean the same as GSI. This generally applies to any use of the other terms as well (LID, SUDS, WSUD etc.), although the overlap in conceptual substance is not perfect.

A list of SCMs that are relevant for building GSI is presented in **Table 2**, with a description of their main modes of operation, their main impacts on stormwater system performance, and the main co-benefits they can deliver (i.e. benefits not directly related to stormwater system performance). Note that both benefits to stormwater systems and co-benefits are context dependant, i.e. dependant on local conditions. Note also the significant differences between SCMs in all three columns, implying that the benefits of GSI depend on the type of SCM employed, while combining SCM types offers a broader palette of benefits.

On a conceptual level many researchers strongly believe that GSI is "The Answer" to the question of how to achieve sustainable and liveable cities against the challenges of increasing urbanization and climate change (Frantzeskaki, 2019; Lafortezza and Sanesi, 2018). Only few draw attention to the drawbacks of GSI, e.g. due to inevitable compromises with regards to how well functionalities are delivered in multifunctional systems compared to monofunctional (Hoang and Fenner, 2015), or the necessary trade-off between water savings, energy consumption and land use (Makropoulos and Butler, 2010).

Table 2: Overview of SCM types and their main attributes.

Type of SCM	Main modes of operation	Main impact on stormwater system performance	Main co-benefits
Green roof	Detention, Filtration, Evaporation	Reduced annual runoff volume, Reduced pollution load in runoff**	Aesthetics, Habitat, Reduced Urban Heat Island effect, Reduced energy consumption in buildings
(Grassed / vegetated) swale	Detention, Transport	Reduced annual runoff volume, Reduced peak runoff, Reduced pollution load in runoff**	Aesthetics, Habitat
Bioretention unit	Detention, Filtration, Infiltration, Evaporation	Reduced annual runoff volume, Reduced peak runoff, Reduced pollution load in runoff**	Aesthetics, Habitat, Increased recharge to groundwater*
Permeable paving	Detention, Infiltration	Reduced annual runoff volume	(Aesthetics), Increased recharge to groundwater*
Pond	Detention	Reduced peak runoff, Reduced pollution load in runoff**	(Aesthetics, Habitat)
Temporary inundation space	Detention	Reduced peak runoff	(Aesthetics, Habitat), Reduced investments due to multifunctional use of space
Rain barrel	Detention, Consumption	Reduced annual runoff volume	Reduced water consumption
Fascine/ soakaway/ soakwell	Detention, Infiltration	Reduced annual runoff volume, Reduced peak runoff	Increased recharge to groundwater*

* This is only a benefit in areas where groundwater needs recharge; there are places where this becomes a drawback due to already high groundwater levels, see Section “Urban Hydrology”.
** The capability of SCMs to reduce pollution varies considerably, and nutrient load may actually be higher after percolating through soil media of e.g. green roofs and bioretention units.

Nonetheless, evidence is mounting to the advantages of combining grey and green infrastructure (Siekmann and Siekmann, 2013; Zhang et al., 2015; Zhou et al., 2018). Documented improvements to pipe-based drainage systems achieved by introducing GSI include reduced flooding (Bai et al., 2018; Goncalves et al., 2018; Haghighatafshar et al., 2018; Sörensen and Emilsson, 2019), reduced runoff volumes (Locatelli et al., 2014; Petrucci et al., 2012), lower carbon footprint (Brudler et al., 2016; Spatari et al., 2011), more robustness (Zischg et al., 2017) and flexibility (Eckart et al., 2012), and more.

2.3 The Three Point Approach (3PA)

The 3PA was briefly presented in the introduction but merits a more thorough presentation due to its pivotal role in the tools we have developed in this thesis. So what exactly is it? First of all, as the name indicates, it is an “approach”. The word “Approach” is defined by the Cambridge dictionary as “a way of considering or doing something”; in the case of the 3PA, this “something” was originally adaptation of urban drainage systems to increased risk of flooding due to climate change.

The 3PA was developed by Govert Geldof through his practice as consulting engineer and his PhD studies in “Coping with Complexity in Integrated Water Systems” (Geldof, 2007). An important underlying assumption in developing the approach was that water management and society are part of a complex adaptive system, i.e. a system that adapts its structure to a changing environment, and a system that is non-linear, i.e. that it can be difficult to predict how it will react to different interventions. Another important feature of a complex system is that it develops “at the edge of order and chaos” (Kaufmann, 1993 in Geldof, 2007), and efforts to “force it into order”, e.g. by structuring it, will inevitably result in suboptimal solutions. Essentially, a complex system has no optimum, only local optima, which are both subjective, i.e. dependant on the perspectives and interests of different actors, and transient, i.e. constantly shifting due to changes outside the system boundaries (the so-called context of the system).

This does not mean that a complex system cannot be improved; only that this cannot be done through a desk-top study; it requires negotiations between people. Also, accepting the complexity makes complex systems simpler to approach, and sometimes simple patterns can be observed in complex systems. One such simple pattern in complex system is “self-organized criticality” (Bak, 1996): for crises such as avalanches, earth quakes and floods, there seems to be a linear relationship between the log of their magnitude and the log of their frequency. This pattern is assumed to be generally true for urban floods and used as the basic form of the graphical representation of the 3PA, see **Figure 1**.

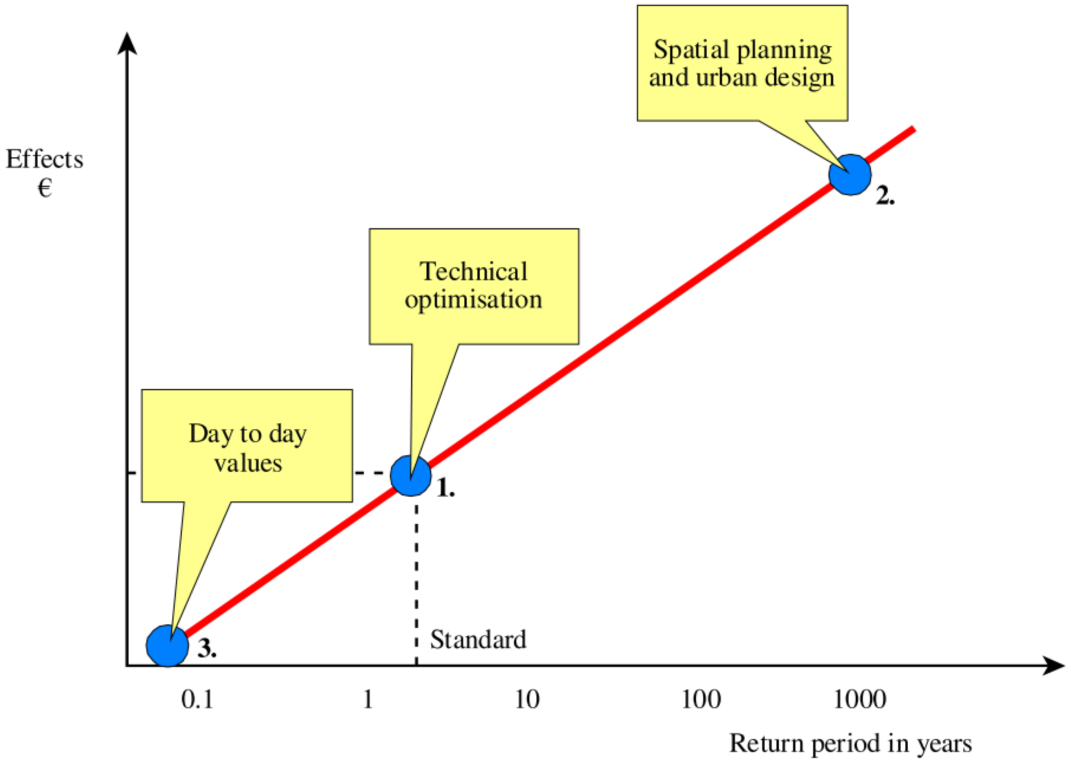


Figure 1: The original 3PA (Geldof, 2007).

An important inference from assuming self-organized criticality of urban floods is that urban floods cannot be *completely avoided* (self-organized critical behaviour cannot be suppressed): urban floods *will* occur, no matter what we do; e.g. when flood hazard is reduced in an area, investments in the area will increase, and thus the flood risk increases again.

On top of the basic form relating frequency to magnitude, Geldof places three points, which represent three discussion arenas, where discussions take place and decisions are made:

1. The first discussion arena has a technical orientation, focusing on formulating and meeting standards for the sewer system, in relation to other urban water systems.
2. The second discussion arena addresses options for reducing damage when the technical systems (inevitably) fail: this requires interaction between water managers and other professionals, leading to new paradigms for spatial planning and improved emergency response.
3. The third discussion arena is oriented beyond water: it is a call for water professionals to connect water issues with other issues in order to give flood-oriented infrastructure (usually placed above ground) a day to day value.

The final message is that flood mitigation activities must address all three points, and will only succeed in the long run when they succeed in the third arena.

Fratini et al. (2012) studied the complexity of decision making in urban flood risk management through in depth interviews with professionals in Denmark and The Netherlands. In two cases reported, the authors introduced the 3PA to organize the decision making process. Based on analysis of interviews with the professionals involved in those cases, the authors concluded that the 3PA was “an efficient communication tool”. In this paper the three “points” are often referred to as “domains” (rather than “discussion arenas”). This paper seems to have contributed to the dissemination of the 3PA into practice; see for example Figure 1.2 in the CIRIA manual for managing flooding from heavy rainfall (Digman et al., 2014).

2.4 Urban Hydrology

Urban drainage professionals seem to consider their field of work as “hydraulics”, thus isolating the study of flows in piped systems from “hydrology”, which becomes synonymous with “natural” water flows. However, “hydrology” is generally defined as the “scientific study of the movement, distribution, and quality of water on Earth” (Wikipedia), which does not exclude water in manmade systems. In this text I will use the term (urban) hydrology to describe (the study of) all water flows in an urban area, natural and manmade alike, including phenomena such as sewer surcharge and flooding.

Modelling both the piped systems and the natural hydrological processes is a complex task, and there is no standardised methodology for accomplishing it (Salvadore et al., 2015). Nonetheless, the interest in integrated modelling of urban hydrology is on the rise (Bach et al., 2014; Fletcher et al., 2013). In Denmark there seem to be two main motivations for expanding the scope of urban hydrology beyond pipes: to study the limits to forced stormwater infiltration and the significance of runoff from vegetated surfaces. Recent advances in these two areas are briefly reviewed below.

Infiltration based SCMs have been promoted as a low-cost and sustainable way of decreasing the pressure on combined sewers, but may cause increases in groundwater levels. Increased groundwater levels are expected to affect the efficiency of infiltration based SCMs (Locatelli et al., 2015; Roldin et al., 2013), increase intrusion of groundwater into drains (intentional as well as unintentional , i.e. leaky sewers), and negatively impact undrained building foundations. A long-term study of the urban hydrology in Copenhagen has shown that the groundwater level has been rising in recent years due to increases in rainfall and decreases in groundwater abstraction (Jeppesen et al., 2011), indicating that large scale stormwater infiltration may exacerbate this trend and contribute to creating the above mentioned problems. A study from another part of Denmark, using a dynamic coupling of a hydrological model and a sewer model, also shows extensive stormwater infiltration can be expected to cause increase in groundwater levels, resulting in increase in drain flow to the sewer system (Kidmose et al., 2015). A study of the urban hydrology in Perth confirms that large scale stormwater infiltration can cause problematically high groundwater levels (Locatelli et al., 2017). This emphasizes the need to account for the constraints presented by groundwater when planning for stormwater infiltration, as demonstrated by e.g. Roldin et al. (2012).

In Denmark, it has been customary to assume zero runoff from vegetated surfaces in the city, and completely remove representation of vegetated surfaces from models used to design sewer systems. With the recent years' focus on pluvial flooding and extreme rainfall it has become clear that runoff from green areas is not always negligible. Studies have been initiated to assess the runoff from different types of urban vegetated surfaces, through computer simulation (Davidsen et al., 2018) as well as in-situ measurements (Nielsen et al., 2017). Preliminary results confirm that green areas may contribute with significant amounts of stormwater runoff under certain conditions.

These two issues contribute further evidence to the recognition that we can no longer “ignore” the natural hydrology in urban areas. The tools we work with impact our understanding of the world, and it can be argued that the popularity of tools such as MIKE URBAN and MOUSE has contributed to the current schism between “hydraulics” and “hydrology”. Thus a more holistic management of urban hydrology probably needs to be supported by tools that reflect the interconnectedness of infrastructure and natural processes.

2.5 Process models

Several models have been proposed to describe the processes surrounding the planning and designing of GSI. The models have varying degrees of complexity and level of abstractness, and they describe the process from different angles, from a planning authority's perspective to the perspective of designing a specific local solution. In the following I briefly review a few models relevant to this thesis.

Fryd et al. (2012) suggested a three dimensional framework for the planning and design of SUDS, see **Figure 2**. It is composed of a triangular base, where each corners represents an axis: a human values axis which can be regarded as a continuum between ecocentric and technocentric worldviews; a space axis which can be regarded as a continuum between small and large physical scales of intervention; and a time axis which refers to different return periods of rain (inspired by the 3PA). The triangle's sides represent domains of operation, e.g. architects form spatial strategies that operate between human values and spatial scales. The vertical dimension represents chronological time, where changes occur in all dimensions of the triangle. The authors state that the framework "provides a line of thought within which to operate"; as such, it is not a practical model for structuring a planning or design process, but rather a didactic tool, aimed to improve interdisciplinary collaboration by illustrating the need for a variety of professional inputs in the process. Intentionally or not, the complexity of the figure also effectively illustrates the complexity of the planning and design situation.

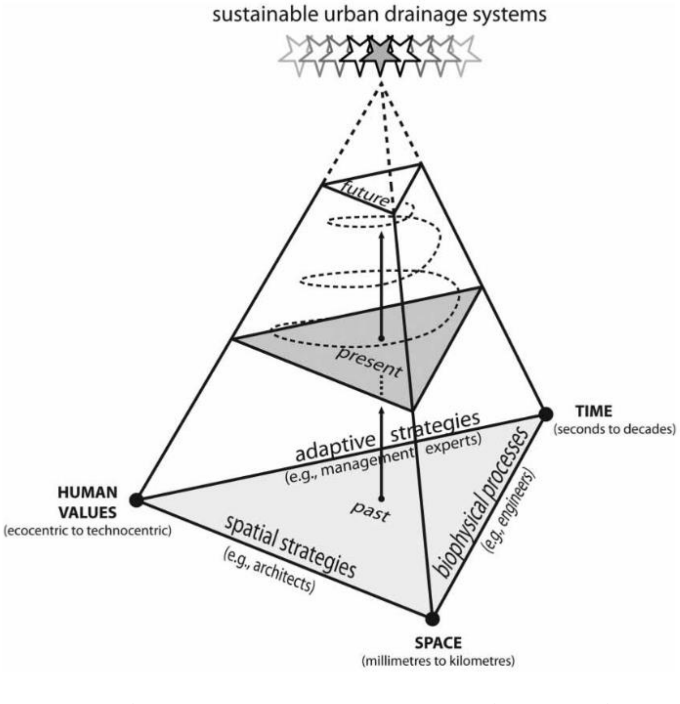


Figure 2: A framework for the planning and design of SUDS, from (Fryd et al., 2012).

"The SUDS manual" (Woods-Ballard et al., 2015, p. 767) provides an example SUDS expenditure profile (see **Figure 3**), where "scheme design" (taking place before construction) is divided into three stages: scheme feasibility and appraisal, preliminary design and (site investigation and) detailed design (with growing costs from stage to stage). Very similar three-stage models of the design process are included in other SCM-related publications (e.g. van de Ven et al., 2016).

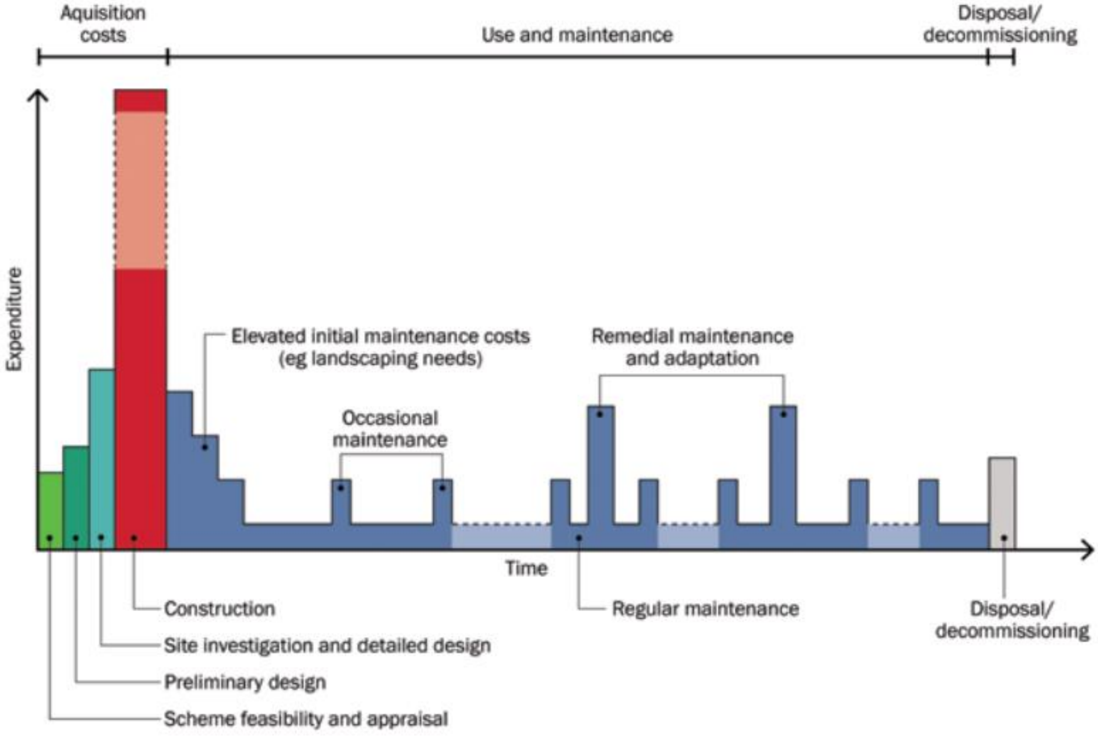


Figure 3: An example SUDS expenditure profile, from (Woods-Ballard et al., 2015).

The schematic illustration of a "traditional design process" for buildings in **Figure 4** (Strømann-Andersen et al., 2012) uses the same fundamental three-stage approach, adding the observation that professional input from an engineer usually happens only in the third and final stage of the design process. In the field of building design, research has shown that "if a reduction in the energy consumption for building operation is the goal, the most efficient approach is to focus on early design decisions" (Landgren et al., 2018). This has motivated the development of guidelines for achieving "integrated design processes" where engineering knowledge is sought included as early as possible to inform better design choices (Landgren et al., 2018). It seems likely that similar dynamics are at play with regards to the design of the space between buildings, i.e. decisions made by the landscape architect / urban planner in the early stages impact the options for managing stormwater on site, such that when an engineer is involved in the last stage, his/her room for manoeuvring is limited and likely to result in more expensive and less optimal and sustainable solutions.

Figure 4: Traditional design process for buildings, from (Strømann-Andersen et al., 2012).

3 Existing tools and methods

3.1 Review of tools (Paper I)

In order to avoid “re-inventing the wheel” with our own tool development, it was important to gain a good overview of already existing tools. This initial overview is presented in Paper I (published in 2015); the following is a short summary of the paper, updated and contrasted with more recent reviews and tools.

Our review

The methodology for achieving an overview consisted of searching the literature and reading papers that seemed relevant. In the papers I read I looked up references that seemed relevant and read them, and I also looked up references mentioned by colleagues that didn’t necessarily show up in the formal search. Despite efforts to cover as broadly as possible I believe that there are tools that were not captured by the search methods, either because they used terms that were outside the search criteria or were not included in the database used, or because they simply were not described in a scientific article in English. For example we have heard of tools developed and used in Germany that never showed up in the literature I covered. Nonetheless, the search revealed a large variety of tools, and it seems unlikely that uncovered tools would significantly change the overall picture that emerged.

The picture was initially quite confusing, showing a myriad of tools that claimed to support decision making with regards to GSI, but did so in very different ways. In order to create order in the chaos I devised a categorization scheme based on the type of question that the tool could assist in answering. I defined three overall types of questions: “how much” (water, pollution, etc. can be managed via SCMs), “where” (to situate SCMs) and “which” (SCM is the best). Some tools addressed a combination of these questions, and each tool addressed them in a different way.

I also assessed, for a selection of tools, which Aspects of Water they addressed. Aspects of water is a methodology for mapping perceptions and values in urban stormwater management (Valkman et al., 2008). This analysis also showed much variability between the tools. A few tools addressed only two aspects, and the most “holistic” tools addressed eight aspects (out of twelve). The most “popular” aspects were the Physical and Logical, followed by Chemical and Economic. One aspect was never addressed (Linguistic) and others very rarely (Historical, Psychological and Moral).

The tools differed in many other ways, and it seemed impossible to develop a system that could encompass all the variability. Instead, the paper discusses a few factors that shape the context in which a tool is developed, and, deliberately or unconsciously, contribute to shaping the tool. These include whether the predominant stormwater management system is combined or separate, the depth to groundwater, the legislative and economic framework, and the availability of drinking water resources.

Other important factors that shape the tools, which were not discussed in the paper, include who the intended users are, in what stage of the planning/design process they are, and what spatial scale they are considering. The same type of question will require a different tool depending on these factors. E.g. an engineering consultant developing a strategy for a whole city or an architect making an initial design for a local redevelopment will both need answers to questions of the type “how much runoff can be captured with this solution”, but they will have different skills, resources, mind sets and priorities, and will need a tool that fits with these.

Update on newer reviews and tools

A review with a similar scope to ours was published in 2017 by Kuller et al., analysing what they called “planning support systems for WSUD”. They organized the tools according to three “approaches”, based on the three thematic planes in the framework suggested by Fryd et al. (2012) (see **Figure 2** on page 12): “WSUD as part of the urban water cycle” (with the subgroups water balance models and hydraulic and hydrologic models), “WSUD as part of the urban form” (with the subgroups planning simulators, technology selection and technology evaluation) and “WSUD as part of water governance” (with the subgroups complex system models, transition frameworks, and scenario analysis). Furthermore, they defined a scale going from “low level” to “high level” applications. The review included a few tools that were not included in our review, mainly at the “high level” end of their scale, aimed at supporting vision and strategy development, e.g. DAnCE4Water (Löwe et al., 2017; Rauch et al., 2017). This is indeed a very complex tool, which integrates all the three approaches (water cycle, urban form and water governance) by combining several distinct modelling tools, each quite complex in itself. Ultimately, this complex machine delivers a quantitative performance assessment as output, i.e. it answers the “how much (water)” type of question; nonetheless, through its combination of models it allows to ask more complicated questions such as "what is the best zoning regulation" (if the goal is to reduce flooding).

A very interesting tool mentioned in the review by Kuller et al. (2017) is the climate adaptation support tool presented by van de Ven et al. (2016; Voskamp and van de Ven, 2015). This was categorized by Kuller et al. as a "planning simulator", a subgroup of the category "WSUD as part of the urban form". The term "planning simulator" is very appropriate for this tool, but I would claim that its main strength is that it allows for the evaluation of biophysical processes - the plane that corresponds to the category "WSUD as part of the water cycle", thus challenging the categorization scheme of Kuller et al. (2017). The tool enables planners to assess the impact of an SCM-plan (which can be sketched interactively on a so-called MapTable, a touch table tailored to GIS) on five key indicators (chosen to reflect the resilience enhancing potential of so-called blue-green adaptation measures): evaporation rate on a hot summer day (for cooling), water retention volume, peak discharge reduction, seasonal water storage at the onset of a drought period, and added groundwater recharge. Unfortunately, the papers describing this tool do not include any details as to how the key indicators are calculated; in the first paper the reader is referred to a report that is not publically available, in the second paper there are only 4 pages of supplemental material briefly presenting the approach used to quantify each indicator. Based on personal communication with the authors (at a the ECCA conference, 2015), I can disclose that the tool is proprietary to the company Deltares and only used in-house, i.e. during consultancy projects performed by Deltares, and there were no plans for making it publically available.

I have not found other recent reviews that deal with the broad spectrum of decision support tools, but a couple of recent articles review the development within hydrological models that enable representation of SCMs (the "how much (water)" category). A review of LID performance by Eckart et al. (2017) included a review of computer models with representation of LIDs. Besides the well know models that were also mentioned in our review (SWMM, MUSIC and MOUSE/MIKE URBAN), they mention two models that use the curve number method (and are thus only useful in the US), one that only indirectly simulates aggregated LID impact (through altering catchment properties), one general optimization tool and one tool that is not available to the public. Thus, according to this review, the only noteworthy change within the field of "how much water"-tools since our review was the introduction of an LID-toolbox in SWMM. Similarly, at the time of publication of the review by Eckart et al., MIKE URBAN had also been upgraded with an LID-toolbox (in the 2016 release), but the authors apparently did not know this at the time of writing.

A more thorough review of models "with the ability to model the hydrologic and hydraulic aspects of LIDs" was published by Kaykhosravi et al. in 2018. This review includes 11 models, of which four were also described in the keystone review from 2007 by Elliott and Trowsdale: an online tool called the Water Balance Model (developed by the British Columbia Inter-Governmental Partnership), the Source Loading And Management Model (developed by the University of Alabama), MOUSE/MIKE URBAN (by DHI) and SWMM/PCSWMM (by the US EPA/CHI). The first model is a rather lumped, conceptual model that focuses on the potential of SCMs to reduce runoff generation, and does not include any hydraulic calculations. The second model is also rather lumped and conceptual, with a focus on runoff quality and the potential of SCMs to control pollutants close to the source. The last two models, MIKE URBAN and SWMM, seem to remain the only options if one wishes to model SCMs and their interactions with piped stormwater systems; the other models mentioned seem to be either very specialized (such as HYDRUS, which allows for analysing water flow, heat and solute transport in porous media) or very general, allowing only indirect representation of SCMs (such as HEC-HMS and SWAT, where SCMs are represented via changes to catchment properties).

Numerous articles describing new tools, methods and models for SCMs are published every year; I shall mention just a few recent examples in order to illustrate the span. Wang et al. (2017) presented "A Diagnostic Decision Support System for BMP Selection", which is composed of several elements, including a model that analyses where the major sources of runoff volume and pollution are in the catchment and a model that suggests which types of SCM are most appropriate at any location. Alves et al. (2018) presented a framework that combines stakeholders' perceptions into the choice of SCM in order to maximize human well-being from co-benefits. And Garcia-Cuerva et al. (2018) developed a methodology where they first identified sites with low income and high pedestrian traffic and then assessed the impact of realistic LID implementations at these sites on the watershed hydrology.

3.2 Tools tested

Besides reading up on tools published in the literature, I have tested some tools in practice by applying them to relevant cases in Denmark. This has mostly been done through student projects (BSc/MSc thesis), where I co-supervised the projects together with one or more senior faculty members and one or more employees from private enterprises (usually a utility company or a consulting company). **Table 3** presents an overall characterization of the tools tested, and the text below describes my perception of the tools' strengths and weaknesses.

Table 3: Characterization of tools applied and evaluated during this PhD-project (through student projects).

Tool (available from)	**Rainfall Domain**	**Spatial scale**	**Goals/ Questions**	**Application Stage**	**User type**
MUSIC[1]	All	Medium	(How much) Water Quantity, Water Quality – in SCMs	Late (informing design)	Engineers
SWMM with LID[2]	All	Local to medium	(How much) Water Quantity, Water Quality – in sewer system	Early and Late (informing strategy and design)	Engineers
BMP siting tool[3]	-	Local to medium	(Where)	Early (informing strategy)	Engineers/ geographers
SCM-dimensioning spreadsheet[4]	All	Local	(How much) Water Quantity – in SCMs	Late (informing design)	Anyone
MIKE URBAN with LID module[5]	All	Medium	(How much) Water Quantity – in sewer system	Early and Late (informing strategy and design)	Engineers
MIKE SHE[6]	All	Local to medium	(How much) Water Quantity – under ground	Early and Late (informing strategy and design)	Engineers/ geographers
SCALGO Live[7]	Mostly C	Medium	(How much) Water Quantity – on surface	Early (informing strategy)	Anyone

[1] ewater.org.au/products/music; [2] epa.gov/water-research/storm-water-management-model-swmm; [3] epa.gov/water-research/best-management-practices-bmps-siting-tool; [4] ida.dk/om-ida/spildevandskomiteen/skrifter#se-og-hent-skrifter; [5] mikepoweredbydhi.com/products/mike-urban; [6] mikepoweredbydhi.com/products/mike-she; [7] scalgo.com/da/live-flood-risk

The characterization table starts with three columns inspired by the framework developed by Madsen et al. (2018) for characterizing climate change adaptation. This framework recommends being specific about the event magnitude, spatial scale and goals of climate adaptation strategies. Here I use the term rainfall domain instead of event magnitude since it gives a more clear reference to the 3PA. Almost all of the tools tested are considered to be useful for all three domains of the 3PA. One exception is the BMP siting tool, which does not directly consider what rainfall magnitude the SCMs can accommodate. The other exception is SCALGO Live, which is most suitable for situations of extreme flooding.

For spatial scale I use the original division into small (from cadastre through home owners' association to neighbourhood), medium (entities such as city, municipality or watershed) and large (from national to international). It quickly becomes evident that none of the tools address the large scale, which is not surprising, since there is little sense in modelling urban hydrology on a scale larger than the urban. Among the tested tools there is a roughly equally large share that address the local scale, the medium scale, or can do both.

When choosing which goal each of the tested tools support it became evident that they all fall into the category water quantity, with a few also addressing water quality, and one falling outside the defined categories (the BMP siting tool). This is not surprising, since my research interest, which guided my choice of tools for testing, was exactly this – how to assist in answering questions regarding "how much water" (where and when). To add a little more nuances to the table I have added a little note regarding the focus of the quantification.

In addition to rainfall domain, spatial scale and goal, I characterize the tools according to which stage of a planning or design process they are most useful at, and what type of professionals they are most useful for. Because stages in a planning process do not necessarily correlate with the three stages generally observed in design processes (see Section 2.5 Process models), I use the broader terms "early" or "late"; for design processes early would translate into sketching and conceptual design, while late would mean conceptual design or project design. Among the tools tested we found some useful for early as well as late stages. The tools tested were mostly developed for engineers (or others with a thorough understanding of hydrological modelling, e.g. geographers), with the exception of two tools developed for a much broader audience (the SCM-dimensioning spreadsheet and SCALGO Live).

MUSIC (Model for Urban Stormwater Improvement Conceptualisation) was the only tool tested that was developed specifically for designing entire (sewer-independent) systems of SCMs, and was doubtlessly the tool that was best for doing so. This is also the tool's greatest drawback, since it does not include the option of modelling a traditional pipe-based stormwater system, thus making it impossible to study the interactions between SCMs and a pipe-based system (a necessity in any retrofit application). Other minor drawbacks include the lack of a geo-referenced user interface (which seems to be an industry standard in Denmark, probably coupled to the high degree of digitization), and the lack of post-processing tools that can represent the results in ways that are easily interpretable by professionals (such as yearly water balance, frequency of overflow, etc.).

The inclusion of an LID module in the rainfall-runoff module of SWMM (StromWater Management Model) enables exactly the kind of analysis that MUSIC lacks: the impact of SCMs on flows in the sewer system and, ultimately, into the receiving waters. The model structure assumes that SCMs will be implemented as individual units mainly on private properties, in dimensions that will only partially manage the water locally, and thus mainly serve to reduce and slow down the flow into the pipe-based sewer system. It allows the user to rather easily specify different degrees of implementation of such SCMs in the watershed and study their cumulative impact. The drawback here is that this model structure makes it very complicated to represent more complex systems of SCMs, those that go beyond the single lot and combine SCMs in treatment trains.

The BMP siting tool is part of the SUSTAIN tool package (System for Urban Stormwater Treatment and Analysis INtegration) (Lee et al., 2012; Shoemaker et al., 2009), developed by the US EPA. It combines information from different GIS layers to produce an output map of urban spots suitable for different types of SCMs. The tool was very sensitive to the format of the input data and could not process the Danish data; instead, we developed our own analysis methods mimicking the BMP siting tool. I assess that the resulting maps would be of limited value to planning professionals in Denmark due to the technocratic "black-box" approach, which includes a limited set of predefined physical parameters, and excludes "soft" parameters that would likely impact the choice of locations in real-world planning processes (see also the discussion in Section 5.2 Approaches to tool development).

The spreadsheet-based tool released by the Danish Society of Engineers for sizing infiltration-based SCMs (in Danish: LAR-dimensioneringsarket) works well for its declared purpose: sizing individual SCMs. It falls short as soon as the design ambition goes beyond single SCMs, although it can be “tweaked” to size slightly more complex structures, as we did in Paper III.

An attempt to model a housing association scale SCM scheme in MIKE SHE revealed difficulties in representing forced infiltration. The MIKE SHE software package is designed for simulating natural catchment hydrology and offers a choice of several different surface partitioning schemes. In order to include forced infiltration from SCMs we had to make several workarounds, which introduced a degree of uncertainty that is difficult to assess.

The rather new tool SCALGO Live has quickly gained impressive market shares in Danish utility and consulting companies, effectively “disrupting” traditional ways of working with flood screening and flood protection planning. We tested its usability for urban designers with the result that the studio we worked with purchased a license for the tool, indicating how useful they found it for their work. The tool makes substantial simplifications in calculating overland flow by treating the earth as a “glass plate” (no infiltration, no roughness); this entails a large theoretical uncertainty about the accuracy of the results, but this also allows the tool to make extremely fast calculations. Furthermore, the tool has an extremely intuitive user interface, and it produces high quality visual output. This makes it accessible to non-specialist users such as urban designers, giving them a significantly better tool for understanding water flow at the location of interest than they had before.

In conclusion, all the tools were useful in some context, but none of the tools delivered the type of functionalities that we saw a need for. Therefore, we continued developing our own tools, as described in the following section.

4 Tools and methods developed

An overview of the tools and methods developed throughout this project is presented in **Table 4** below, and each tool is presented in more detail in the following subsections. **Table 4** includes the same columns as **Table 3**, which presented the tools tested during the project (for the rationale behind the columns see Section 3.2 Tools tested).

The tools we developed, like the tools we tested, generally have the flexibility to address all rainfall domains; the only exception here is the Characteristic Rain Events (CREs), which was specifically developed to support designers in achieving better aesthetics during the day-to-day experience of the SCM, i.e. in domain A. The tools are evenly distributed between the small and medium spatial scales, and all of them are designed to answer the question "how much water" – with subtle differences in which flows are in focus. Three of the four tools are designed to be applied in early stages of planning and design, the exception again being the CRE, developed to assist in the detailed design stage. Some of the tools are designed to be used by engineers and others by designers.

Table 4: Characterization of tools and methods developed throughout the project.

Tool/ Method	Rainfall Domain	Spatial scale	Goals/ Questions	Application Stage	User type
Quantified 3PA (Paper II)	All	Medium	(how much) Water Quantity – in SCMs	Early (informing strategy)	Engineers
CRE (Paper III)	Focus on A	Small	(how much) Water Quantity – and aesthetic pleasure	Late (informing detailed design)	Designers
Extensive modelling (Paper IV)	All	Medium	(how much) Water Quantity – in sewer system	Early (informing strategy)	Engineers
SCM-potential (Paper V)	All	Small	(how much) Water Quantity – in SCMs	Early (informing initial design)	Designers, planners and engineers

4.1 Quantifying the 3PA (Paper II)

The first operationalization of the 3PA that we attempted is presented in Paper II. The paper includes two parts: 1) an analysis of Danish rainfall series that produced numbers for the axes of the 3PA, and 2) a set of metrics designed to characterize the impact of SCM scenarios at the urban scale.

The first part was originally done in order to enable the second part, but today stands as the main output: the quantitative definition of the three domains of the 3PA proved extremely useful, it has been widely adopted in practice, and it opened up for the development of all the subsequent tools and methods in this project. The key results are all present in **Figure 5** below.

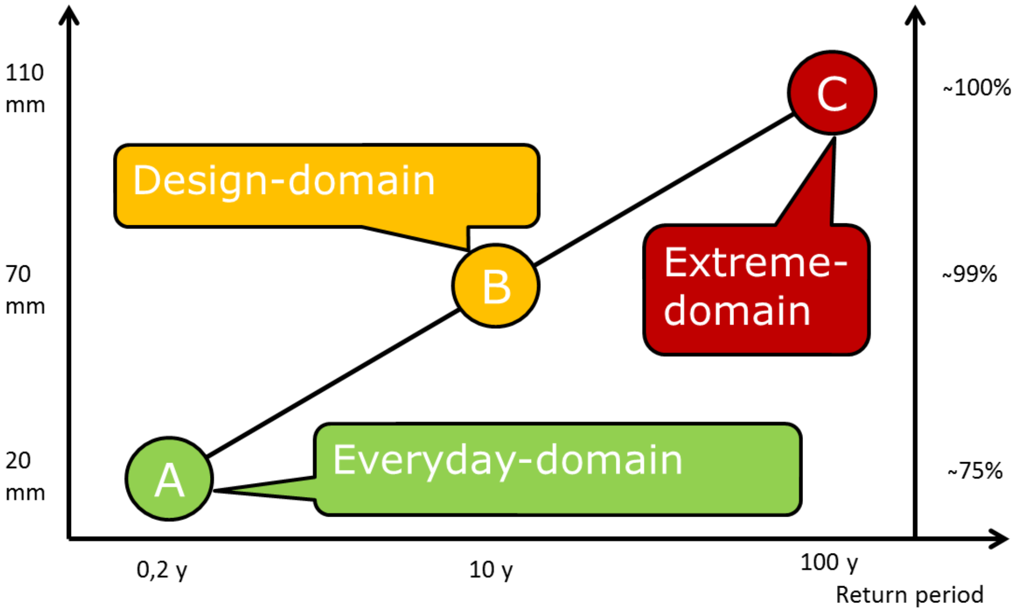


Figure 5: The main result from Paper II - a quantified version of the 3PA based on statistical analysis of Danish rainfall series (from the paper, with slightly different layout). The horizontal axis shows the return periods that are used to define the three domains; the left vertical axis shows the rainfall depth that caps the upper boundary of each domain, while the right vertical axis shows the fraction of the yearly rainfall depth that falls within each domain.

This figure differs from the original version of the 3PA (compare to **Figure 1**) in terms of nomenclature of the domains, definition of a specific return period for each domain on the horizontal axis, and providing two sets of magnitudes for the vertical axis. The labelling of the domains was changed from numbers to letters in order to ease communication: firstly because with the introduction of numbers on all the axes it was more convenient to separate the domains from their quantifications by addressing them with letters, and secondly we wanted to rectify the engineering-bias embedded in designating domain B as the first domain and replace it with the more neutral and practical order of ascending magnitudes.

The return periods that “cap” each domain were chosen based on current Danish paradigms: the return period of 0.2 years for domain A stems from the design guideline for rainwater harvesting systems, the return period of 10 years for domain B equals the recommended service level of combined sewers (surcharge), and the return period of 100 years for domain C equals the service level recently adopted by Copenhagen for extreme events (flooding). Using these return period definitions and a selection of historical records from the Danish network of high resolution rain gauges we calculated a representative rainfall depth for each domain, and then calculated the share of each domain in the annual rainfall depth.

The results show for example that domain A, formerly labelled “point 3”, is characterized by rain events of 20 mm or less, and the aggregated depth of all rainfall events that are 20 mm or less corresponds to 75% of the total annual rainfall depth. The quantified 3PA includes a total of nine numbers (three return periods, three event depths and three fractions of yearly rainfall), which is relatively easy to remember, and provides a versatile “rule of thumb” for discussing dimensions of SCMs. The numbers are, of course, only valid for Denmark, but the methodology can easily be replicated for any other region with a sound record of rainfall. I have not seen any tool reminiscent of this in the literature.

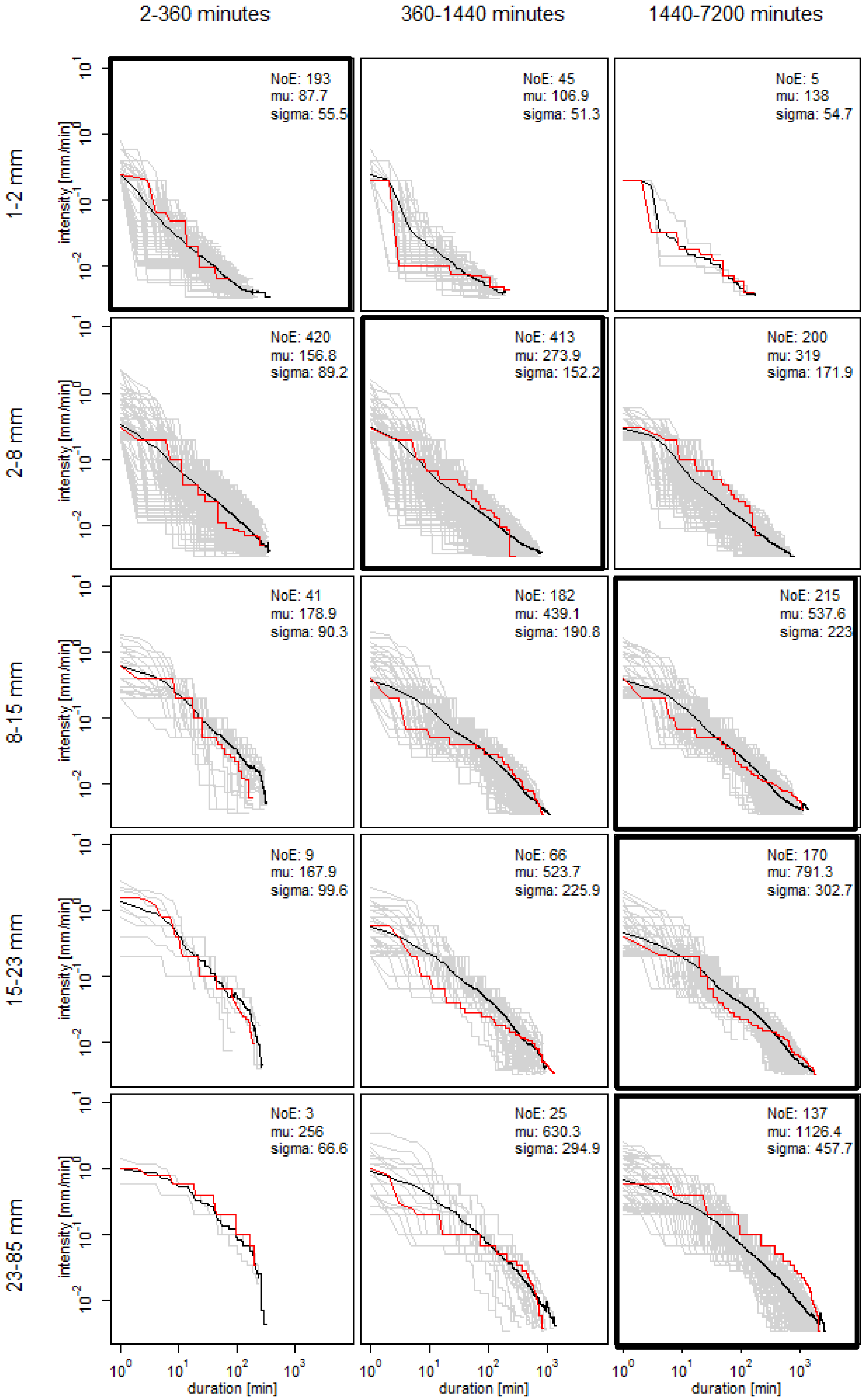
The second part of the paper defines and quantifies a set of efficiency metrics for SCMs at the urban scale: how much rainfall can they potentially manage, how much drinking water supply can they replace, and how much can they reduce the inflow to the wastewater treatment plant. Similar studies, investigating the theoretical, maximal impact of SCMs under varying constraints and against varying performance indicators, are numerous in the literature; the novelty of this approach lies mainly in that we calculated efficiency metrics for each domain. In this way we tried to illustrate that SCMs designed to manage frequent rains have limited impact when the heavier rains come – an understanding that is self-evident to drainage professionals but seems to elude other professionals. However, we have realized that the way we presented the results was not very intuitive to understand, and we have used this lesson to improve the clarity of results in the subsequent tools we developed.

4.2 Characteristic Rain Events (Paper III)

The second tool/method we developed, the Characteristic Rain Events (CRE), is presented in Paper III. This tool also draws heavily on the 3PA and analysis of rainfall series, but presents the results in a very different manner. The difference in presentation approach is largely due to the fact that the idea originated in the mind of an urban designer rather than an engineer (the first author, Jonas Smit Andersen). Jonas had been working as a consultant operating in the field between architects and engineers, and saw this need for visualizing how rains differ in their manifestation in order to enable designers to better "stage" rainwater in their SCMs. We helped him develop a scientifically sound method for choosing single, historical rain events that can be claimed to represent different types of rain. Furthermore we helped him develop a simple hydrological model that "translates" CREs into extent of visible rainwater in an SCM, and thus can be used as a tool for improving the SCM design.

The method we developed for choosing characteristic rain events from a long-term record included four steps: 1. Aggregating rain events using a dry weather threshold of 24 hours (the maximum time it generally should take for an SCM to regain its capacity after a rain event); 2. Allocating rain events to 15 categories, which were defined by 5 rows of return periods (four categories within domain A and one in domain B) and 3 columns of event durations (x<6 h, 6<x<12, 12<x); 3. Identifying the most characteristic rain event within each category based on proximity to a mean rainfall intensity distribution calculated for each category; 4. Selecting the final CRE in each row based on the number of events in each category of the row. **Figure 6** below illustrates the matrix of 15 categories, with the events in each category plotted according to their intensity distribution.

Figure 6 (next page): Rain events from a 36-years rain record categorized according to event depth (rows) and event duration (columns), plotted based on intensity distribution. Grey lines represent historical events, black lines represent the calculated mean intensity event of each category, and red lines represent the historical event that most resembles the mean event of its category. Bold frames indicate the categories from which the final CREs were chosen. NoE = Number of events; mu = mean event duration; sigma = standard deviation of the event duration. From Paper III.


2-360 minutes
360-1440 minutes
1440-7200 minutes
1-2 mm
2-8 mm
8-15 mm
15-23 mm
23-85 mm
intensity [mm/min]
10^{1}
10^{0}
10^{-1}
10^{-2}
NoE: 193
mu: 87.7
sigma: 55.5
NoE: 45
mu: 106.9
sigma: 51.3
NoE: 5
mu: 138
sigma: 54.7
NoE: 420
mu: 156.8
sigma: 89.2
NoE: 413
mu: 273.9
sigma: 152.2
NoE: 200
mu: 319
sigma: 171.9
NoE: 41
mu: 178.9
sigma: 90.3
NoE: 182
mu: 439.1
sigma: 190.8
NoE: 215
mu: 537.6
sigma: 223
NoE: 9
mu: 167.9
sigma: 99.6
NoE: 66
mu: 523.7
sigma: 225.9
NoE: 170
mu: 791.3
sigma: 302.7
NoE: 3
mu: 256
sigma: 66.6
NoE: 25
mu: 630.3
sigma: 294.9
NoE: 137
mu: 1126.4
sigma: 457.7
10^{0}
10^{1}
10^{2}
10^{3}
duration [min]

The final five CREs range in duration from about one hour to three consecutive days. The long durations are influenced by the relatively long threshold of dry weather we used (24 hours). However, our analysis shows that using 12 or 48 hour thresholds did not change the results significantly. None of the chosen CREs contains anywhere close to 24 hours of consecutive dry weather; the longest dry weather period within a CRE is about 12 hours.

The event that can be said to be “most typical” of all is CRE 2: it stems from a category that includes a stunning 49% of all events. It has a duration of 15 hours and a total depth of 6 mm. As can be seen from figure 7 in the paper, it contains a little “prologue” in the beginning of the event of about one millimetre, a break of about 9 hours, a substantial rain for about 2 hours mounting to about four millimetres, a shorter break of about 2 hours, and a little “epilogue” of about one millimetre.

When this rain is fed to the hydrological model it produces visible water in the smallest depressions of the example SCM for more than two days, thus successfully “staging” the water. This may be a bit misleading, because this SCM was designed by a very experienced landscape architect and optimized to stage “daily rain” (rain from domain A). Had this SCM been designed by the average engineer or architect, it would probably include much larger depressions, where CRE 2 would disappear immediately, not producing any visible water surface. In the future, for educational purposes, I would include an example of such a “standard” design alongside the optimized design to more clearly illustrate the value of using CREs in the design process.

I have not seen any tool that resembles the CREs in the literature. The hydrological model has no novelty, it follows completely standard hydrological process models; we coded it ourselves because this allowed us the flexibility to easily adapt it to the specific SCM design and easily extract the results relevant for assessing the visibility of water.

4.3 3PA-structure for detailed modelling studies (Paper IV)

The next paper, Paper IV, presents a methodology which makes use of several existing modelling tools. Again, the 3PA was used as a guiding principle, this time to structure an extensive study of ways to improve the ongoing retrofitting of the Skt. Kjeld neighbourhood.

The Skt. Kjeld neighbourhood or the Ydre Østerbro cloudburst branch (roughly overlapping), depicted in **Figure 7**, was declared to become the “first climate adapted neighbourhood in Copenhagen” in 2011. What exactly this means and how to achieve it has been continuously taking shape ever since, influenced by bottom-up activities supported by the local urban regeneration office, top-down planning documents from the city administration, ad-hoc projects, etc.

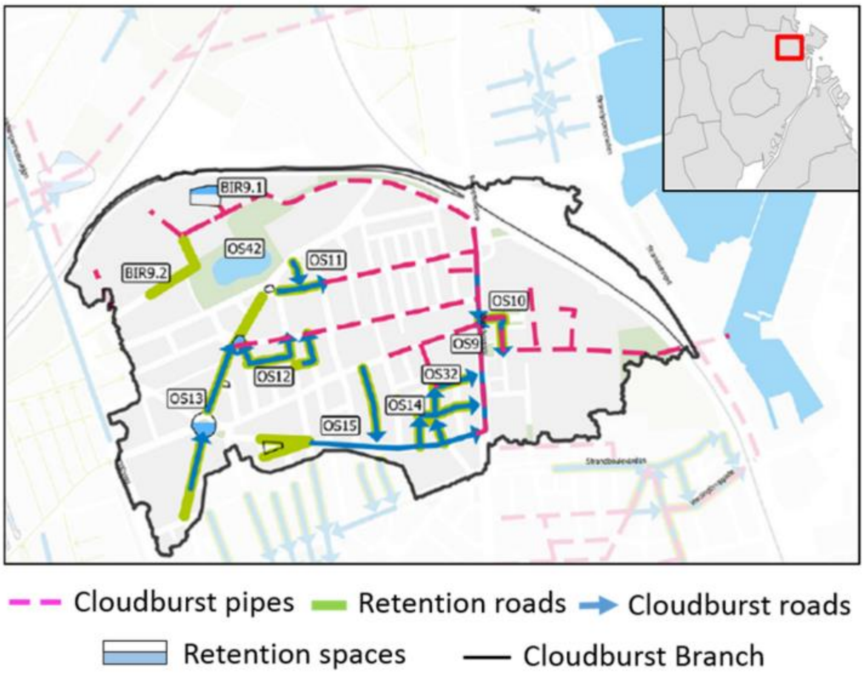


Figure 7: A map of the Ydre Østerbro Cloudburst Branch. From Paper IV (adapted from City of Copenhagen, 2015).

At the time of the study, the latest relevant planning document, referred to in the paper as the cloudburst management plan (CMP), designated a series of streets to become “cloudburst roads” (road profile redesigned to allow transport of water on its surface) or “retention roads” (road redesigned to feature water retaining elements including bioretention units and other types of GSI). The CMP also indicated the extent of a future network of “cloudburst pipes” (underground drainage pipes with the main purpose of transporting runoff during extreme rainfall events). A “cloudburst tunnel”, i.e. a very large pipe that enables discharge of runoff from the catchment directly to the harbour, was already under construction (and has since been completed). We took this retrofit plan as outset for our study, and developed a series of scenarios that incrementally extended the planned cloudburst infrastructure including use of GSI and redirected runoff from the combined sewer system to the cloudburst infrastructure.

We assessed the impact of each scenario, from baseline (BL) to most extensive retrofit (S4), by modelling them in the software packages MIKE URBAN and MIKE FLOOD (by DHI). For assessing the scenarios' compliance with expectations in domain B we simulated the systems' response to a 10 years rain event (using a design storm generated with appropriate factors to account for climate change and model uncertainty) and calculated the fraction of surcharging maholes. For assessing the scenarios' compliance with expectations in domain C we simulated the systems' response to a 100 years rain event (again using a design storm with appropriate factors) and calculated the extent of flooding. These two approaches are in accordance with state-of-the-art modelling standards in Denmark, with the minor novelty of our study being first to include the new LID module in MIKE URBAN, and using a different rainfall-runoff module than the standard (including green surfaces).

The main novelty of our study lies in the approach for assessing the scenarios' compliance with expectations in domain A. This domain is normally ignored in this type of analysis and planning. To this end we simulated the stormwater runoff processes and sewer network flows in the systems during a whole year. This task was challenging mainly due to its heavy computational demands, including managing the very large datasets that were produced as output. Other technical issues included generating long term time series of boundary conditions and removing the rather significant amounts of "numerical water" that is generated when the simulation runs through dry weather periods. Finally, selected output time series were compiled and analysed to produce an annual water balance – the flow partitioning of the rainfall that hits the catchment over an entire (and supposedly representative) year, see **Figure 8**.

The results for domain A show that the last scenario proposed (S4) is able to shift the water balance significantly compared to the baseline scenario (BL), reducing the flow to the WWTP from 50% of the rainfall to 29% of the rainfall (a relative reduction of 40%). If such a shift could be achieved in other neighbourhoods of Copenhagen as well (we believe it could), this would entail significant improvements to the sustainability of the integrated system of sewers and WWTP, including better energy efficiency and reduced overflows. Note that this is a synergistic result, achieved together with the goal of reducing surcharge (domain B) and reducing flooding (domain C). The result thus underlines the value of including domain A in strategy development, in this case through exploitation of already planned cloudburst infrastructure beyond its primary function with respect to flood control. The results will hopefully inspire relevant planning authorities to overcome the administrative and legal barriers for such exploitation.

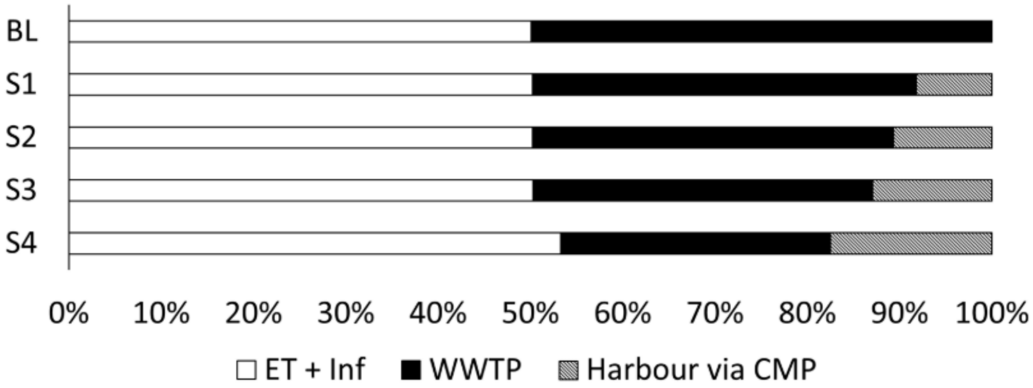


Figure 8: Annual water balance of the scenarios simulated for Ydre Østerbro cloudburst branch, from Paper IV. ET stands for Evapotranspiration, Inf stands for Infiltration, WWTP stands for Wastewater Treatment Plant, and CMP stands for Cloudburst Management Plan infrastructure.

Increases in infiltration and evapotranspiration, from the implementation of infiltration-based SCMs, amount to 3% of the annual rainfall in the last scenario. This may seem surprisingly little in the context of a PhD focused on SCMs. Indeed, at the outset of this study we intended for SCMs to play a larger role, but it was also important for us to make the scenarios realistic. A major impediment we encountered was that the municipality of Copenhagen does not allow infiltration of road runoff due to worries about polluting the groundwater with de-icing salts. One solution to this could be to construct swales or bump-out rain gardens that are lined at their bottom, so that runoff is filtered through the soil and subsequently drained through the cloudburst infrastructure to the harbour. In this manner we would expect the water reaching the harbour to be significantly cleaner in terms of heavy metals, PAH’s and other road-related pollutants, although the nutrient load may not necessarily be reduced.

Unfortunately due to a bug in the software such a solution could not be modelled. I expect that bottom-sealed SCMs would have insignificant impact on the model outputs. A small shift in the water balance from discharge to receiving waters to evapotranspiration would probably appear, but has no functional value in this catchment: once runoff is moved from the combined system to the cloudburst infrastructure, there is no motivation to limit the flow because the cloudburst infrastructure is dimensioned to cope with extreme events and the receiving water (the harbour) is rather insensitive to water quantities. Notwithstanding, I would still strongly recommend the implementation of SCMs in order to improve the quality of the runoff before it is released to the harbour.

This study illustrates that even the most advanced modelling tools for urban hydrology, such as MIKE URBAN, have limitations when it comes to properly representing SCMs. The limitations are most severe when it comes to addressing domain A of the 3PA, which is not surprising given the fact that these modelling tools were developed mainly in order to support the "technical optimization" of piped-based systems – the focus of domain B. The time and effort put into the development of this model, and especially into the production of the water balance results, were immense. It would be a good idea to develop faster methods or tools for real-life applications.

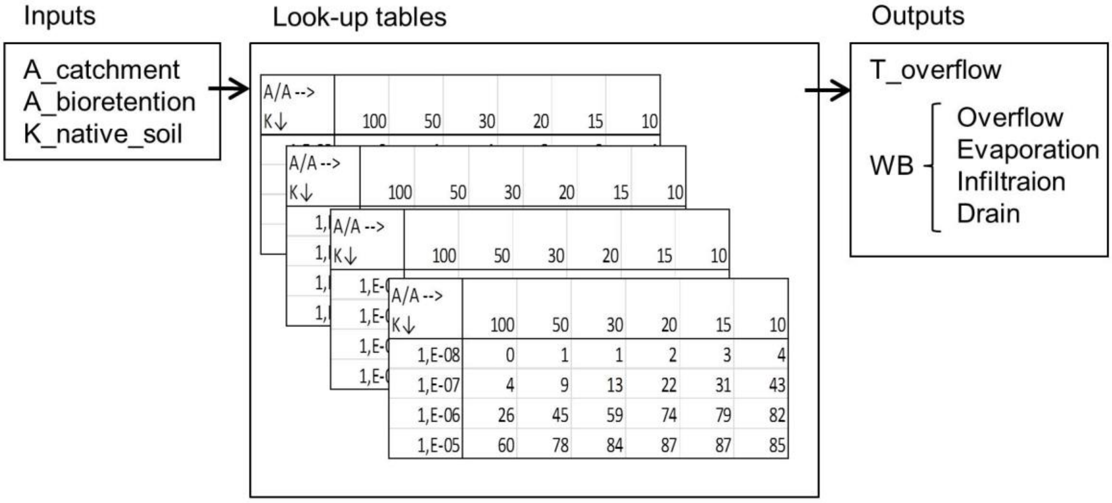
4.4 SCM-potential (Paper V)

Last but not least, Paper V presents a concept for a tool we call SCM-potential, developed to support planners, architects and engineers in early stages of local (re)development projects. The tool has so far reached a "proof of concept" level (Technology Readiness Level III), meaning that we have demonstrated that the idea is feasible. The tool has been applied on several case studies and demonstrated at several workshops, generally receiving positive feedback and interest from participants.

The basic idea with the SCM-potential tool is to allow users to explore the potential of SCMs in a given project area, which could be a single lot, a street, a block or similar small-scale area. By "explore the potential" we mean looking at how much space can be reasonably dedicated to SCMs (based on visual inspection of a map and taking into account other functions and their space requirements), and getting an assessment of the hydrological impact of these SCMs.

This approach is opposite to the standard approach, which would be to look up what are the criteria for managing runoff from a given area, calculate how large a given type of SCM must be in order to manage this much runoff, and then force that SCM into the area (or realize there isn't enough space for that). Our approach is more compatible with the way designers work, and gives them more flexibility to incorporate stormwater management among the many other functions and space requirements that they need to juggle. This approach may yield better SCM designs, given that every area poses different physical opportunities and constraints for managing runoff locally, which are overlooked when using a “one rule fits all”-approach (as has been argued by other researchers too, e.g. Petrucci et al. (2016)).

The envisioned user interface allows the user to draw the outline of SCMs on a map, thus interactively exploring the cumulative area that can be allocated to SCMs. The tool currently features four different types of SCMs: permeable surfaces, rain gardens, bioretention units, and temporary inundation spaces. These SCMs can be applied in series but only in the order listed (with rain gardens and bioretention units being mutually exclusive). The cumulative areas designated to each type of SCM, together with information on the impervious area of the catchment and the hydraulic conductivity of its native soil, are then sent to the SCM-potential calculator. Here the impact of each type of SCM is found through a lookup table, and in case of more than one type of SCM their impacts are added up. The impacts are returned to the user in the form of two outputs: 1) a return period for outflow from the catchment, and 2) an annual water balance; see **Figure 9** for a schematic illustration of the workflow of the tool.



A/A --> K↓	100	50	30	20	15	10
1,E-08	0	1	1	2	3	4
1,E-07	4	9	13	22	31	43
1,E-06	26	45	59	74	79	82
1,E-05	60	78	84	87	87	85

Figure 9: Schematic illustration of the workflow in the SCM-potential tool for assessing the impact of a suggested implementation of bioretention units. A=area, K=hydraulic conductivity, T=return period, WB=water balance.

The return period for outflow from the catchment is presented against a background of the quantified 3PA, see **Figure 10**-A. The rationale for choosing this output is the strong interest in removing stormwater from the combined sewer system in order to avoid it surcharging more often than once every 10 years (main requirement in domain B). This allows the user to quickly assess whether this goal is achieved or, if not, how far the current design is from the goal (thus indicating how realistic it is to reach the goal given the area's constraints).

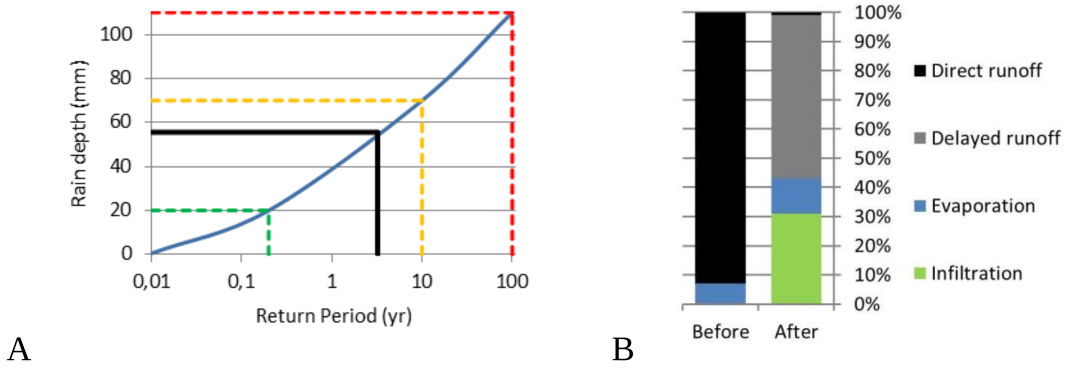


Figure 10: Example output from the SCM-potential calculator.

The annual water balance of the catchment is presented as a stacked bar comprised of the flow fractions "infiltration", "evaporation", "delayed runoff" and "direct runoff", see **Figure 10**-B. "Infiltration" refers to runoff that has exfiltrated from SCMs into the native soil; "evaporation" refers to runoff that has evaporated from an SCM surface or transpired through the vegetation of an SCM; "delayed runoff" is runoff that has been captured in an SCM and released slowly; and "direct runoff" is runoff that has overflowed from an SCM or never entered any SCM. The rationale for choosing this output is to draw attention to the rather significant impact that some SCM configurations may have on the annual water balance, even in cases where they do not meet the common (in Denmark) goal of holding back a 10-year event. Such water balance impact could be characterized as relevant in domain A, for several reasons. In the context of combined sewer systems, every drop of water that is removed from the flow to the WWTP increases the sustainability of the system by reducing costs of operation, and, from a certain return period upwards, reducing overflows (from CSOs as well as at the WWTP). In separate systems, water that has passed through an SCM would generally be expected to have a higher quality and cause less damage to receiving waters. In either case, water that is evaporated generally represents some greening in the catchment, which is expected to add to the area's liveability. If the area is within the watershed of an urban stream, infiltration may add to the baseflow and thereby improve stream health.

The lookup tables enable the tool to deliver results instantaneously and free the user from managing rainfall input. They were created in the following ways: for the permeable surfaces, we made the simplifying assumption that they can handle any rain magnitude that falls directly on them, no more and no less. This allows to simply deducting these areas from the impervious catchment area. If permeable surfaces are the only SCM implemented, then this would have no impact on the return period of overflow. If another SCM is implemented, then the reduced impermeable area would entail better performance for the next SCM. Permeable surfaces will in any way impact the water balance of the area.

The difference between rain gardens and bioretention units, as implemented in the SCM-potential tool, lies in the subsurface configuration: rain gardens are simply vegetated depressions from which water can percolate into the native soil, whereas bioretention units include a subsurface retention space with a drain function. For each, a series of long term simulations was run in SWMM, varying the catchment-to-SCM area ratio and the native soil conductivity. From the results we extracted the annual water balance and return period of overflow for pairs of area ratio and conductivity. All other design variables were kept fixed at standard sizes in order to keep things simple, under the assumption that the two variables chosen were the dominant ones. A sensitivity study we performed with students (using the LID module in MIKE URBAN, which is in principal identical to the one in SWMM) (Schiolborg and Lindbladh, 2016), confirmed this assumption, as have other studies (e.g. Leimgruber et al., 2018; Petrucci et al., 2016).

For the temporary inundation space, the return period of overflow is interpreted from the quantified 3PA graph based on the return period of the rain event that can be stored in the depression (calculated from the volume of the depression divided by the impervious catchment area). The annual share of the water balance that is delayed is likewise interpreted from the quantified 3PA graph as the share of annual rainfall that is equal to or smaller than the rain event that can be stored in the depression.

To find the combined impact of, for example, a bioretention unit followed by a temporary inundation space, the tool first adds up the rain depth that can be stored in each (for the bioretention unit this is found from the quantified 3PA graph by looking up the rain event depth that corresponds to the return period of overflow). This cumulative depth is then “translated back” to a return period for overflow from the combination of SCMs. To find the impact of combinations of SCMs on the water balance the tool uses a weighted average approach.

As is evident, the tool makes many simplifying assumptions regarding the hydrological performance of SCMs in order to deliver a functionality that is very easy to understand and very fast and simple to use. We argue that these simplifications do not introduce more uncertainty to the results than what is acceptable under the circumstances that it is designed to be used within - early planning and design stages. As discussed earlier, these stages are characterized by limited knowledge. For example, the hydraulic conductivity of the native soil has usually not been investigated yet, and even if a few sample tests have been made, the results are still subject to large uncertainties due to natural soil heterogeneity. Limited time and resources at early phases also entail that it is not realistic to expect that designers use complex tools – the only alternative to a simple tool is no tool, entailing if SCMs are included at all it will be based on qualitative judgement alone.

The concept of the SCM-potential tool is quite similar to the climate adaptation support tool (van de Ven et al., 2016, see Section 3.1 Review of tools (Paper I)). However, as mentioned, this tool is not publically available, so there is still a market for a tool such as SCM-potential. The SCM-potential also bears some similarities to WABILA (WAsserBILAnzmodell, Henrichs et al., 2016), a German tool developed to compare the water balance of individual plots or development areas to pre-development or natural conditions. However, WABILA does not consider return periods of overflow, thus only addressing one of the two key indicators in SCM-potential, and it doesn’t have a graphical user interface, and is therefore not very useful for designers.

5 Methodological reflections

5.1 Revisiting the 3PA

The Three Point Approach has been used extensively in this thesis; it has shaped our work – and our work has shaped it. But are there drawbacks associated with using the 3PA?

In my interpretation, the message of the 3PA can be divided in two: 1) there are three distinct domains of decision making within urban stormwater management, and it is fundamental to be able to distinguish them, and 2) any stormwater project should strive to address all three domains. It seems that the first part of the message has diffused effectively in to Danish practice (Madsen et al., 2018), although a consensus regarding the magnitudes of the domains is still lacking. Unfortunately, the second part of the message seems to get lost: the focus of stakeholders has remained on domains B and C, with domain A rarely addressed (Madsen et al., 2018).

In other words, it seems that the clear distinction of the domains in the 3PA may increase professionals' awareness of which domain they operate in, yet not necessarily increase their awareness to the benefits of considering the other domains in their planning and design processes. On the other hand, it would be naive to think that a simple communication tool alone can change decades of professional paradigms and institutional inertia which support the focus on domain B, or compete with the attention that domain C gets from the public and the politicians after the occurrence of large scale flooding events.

In our work we have tried different ways of drawing attention to the neglected domain A by quantifying hydrological impacts of minor rains. In that process we have modified its original meaning from "day-to-day values" (not necessarily water related) to "everyday rains". In other words, in our attempt to broaden the scope of SCM projects in terms of rainfall domains, we have narrowed the scope of the 3PA from addressing the complex relations between urban form and urban hydrology to addressing only urban hydrology. I would consider it a positive development if our tools and methods get diffused and influence professionals to consider (also) minor rains in their plans and designs; but it would be regrettable if this interpretation of the 3PA overrides the original message about designing SCMs that are truly multifunctional, i.e. have an added value to people's daily lives (beyond managing stormwater).

A problem with the 3PA that has persisted throughout this project was how to name the different domains. The root of the problem lies in the interdisciplinary nature of the tool: the same words mean different things to engineers, landscape designers and urban planners. Using long descriptive names could minimize confusion across professions, but diffusion into practice requires short names. When we changed the names of the domains in paper II compared to the original names used by Fratini et al. (2012) our main intention was to suggest shorter and more "catchy" names (see **Table 5** below). "Domain of technical optimization" became "Design domain", referring to the practice of designing urban drainage pipes to meet regulations for permissible return period of failure. Unfortunately, with our engineering background we oversaw that for landscape architects domain A would be the "Design domain", since they design landscapes with the main aim of pleasing people on a day-to-day basis. "Domain of day-to-day values" became "Everyday domain"; the sub-heading "rainwater resource utilization" hints at our ambition to draw attention to the potential water resources perspective hidden in this domain, but this subheading was never actively used. "Domain of spatial planning and urban resilience" became "Extreme domain", a name that is easy for all to understand and remember, but loses the original message about how extremes should be handled (with spatial planning rather than pipes).

Table 5: Names used to describe the domains of the 3PA in different papers.

	A	**B**	**C**
Original	Domain of day-to-day values	Domain of technical optimization (and standards)	Domain of spatial planning (and urban resilience/ design)
Paper II	Everyday domain: Rainwater resource utilization	Design domain: Urban drainage pipes	Extreme domain: Pluvial flood mitigation
Paper III	Domain A	Domain B	Domain C
Paper IV-V	Everyday domain	Design domain	Extreme domain
New	Local domain	No-surcharge domain	Controlled flood domain

When presenting the CREs (Paper III), a tool dedicated to landscape architects, we evaded the naming problem by simply using the labels A, B and C. In the following papers we have, in lack of better options, used the terms from paper II. Although I do not believe we can ever find a "perfect" set of names, one that can convey the complex reality behind the 3PA in one or two words per domain, I'd like to take this opportunity to suggest a new set.

With the hydrological mind set sat has shaped this thesis, and despite the pitfalls of this mind set as discussed above, the essence of domain A lies in unfolding the potential of rainwater to be used locally: staging it in “artful rainwater design”, harvesting it to reduce drinking water demands, retaining it to minimize adverse impacts downstream, supporting vegetation, and so on. Hence I suggest calling domain A the “Local domain”. Note that such diverse local solutions should not necessarily all be designed for a return period of 0,2 years (as we used to define domain A in the quantified 3PA); the magnitude of this domain should be interpreted according to needs and aims in each case.

The essence of domain B, the essence of most of the standards and regulations and technical optimization, is to provide adequate capacity for containing stormwater runoff, whether that is within underground or over-ground measures, or within conveyance-based or detention-based measures. Hence I suggest calling it the “No-surcharge domain”, or the “No-flood domain”. This definition applies to domain A too, thus domain A cannot be regarded as separate from domain B but rather nested within domain B, which makes sense in many ways.

The essence of domain C is about ensuring that the stormwater runoff that will inevitably flood cities under extreme events will be “gently” directed away from most vulnerable areas to least vulnerable areas, through careful spatial planning and dedicated design of specific urban spaces; or, where adequate surface manipulation is not possible, “firmly” directed away through engineering solutions. Hence I suggest calling domain C the “controlled flood domain”, indicating that some flooding needs to be accepted, but we can and should aim to limit its hazards. This also indicates the existence of a fourth domain, the domain where the flood control measures can no longer cope, uncontrolled flooding occurs and the emergency situation needs to be addressed through non-structural resilience measures (as also suggested by Digman et al., 2014).

5.2 Approaches to tool development

My approach to tool development throughout this project has (clearly) been *keep it simple*, and I have provided a few examples of other tools that go in the same direction (e.g. Henrichs et al., 2016; van de Ven et al., 2016). Meanwhile, there seems to be a continuous production of ever-more “advanced” tools, which are inevitably also more complex (e.g. Löwe et al., 2017; Shoemaker et al., 2009; Wang et al., 2017). There is no doubt that reality gets continuously more complex, but does that necessarily mean that our models of reality need to be more complex? Is a detailed model necessarily *better* than a simple model? The answer to these questions depends, of course, on the purpose of the model (e.g. Jakeman et al., 2006). It is important to distinguish between two fundamentally different purposes: studying a system, i.e. gaining knowledge about interrelations in the system (as done in e.g. Paper IV), and predicting system behaviour, i.e. producing output that can be used for decision making in real life (as done in the SCM-potential tool, Paper V).

Complex tools, often combining multiple complex models, are able to connect innumerable factors shaping urban hydrology, providing opportunity to study complex interrelations and system interdependencies. However, they cannot avoid ending up with large numbers of parameters, becoming “unparsimonious”, combining uncertainties in a manner that makes it hard to assess their magnitude, and in theory impossible to calibrate and validate. This in itself should warn against using them for prediction. Furthermore, they quickly become a “black box”, where the user cannot follow the inner workings of the tool nor has the freedom to change them. As formulated by Geertman (2006): “most planning-support instruments of the last decade do not readily fit the changing needs of the planning profession in that they are far too generic, complex, inflexible, incompatible with the `wicked' nature of most planning tasks, oriented towards technology rather than problems, incompatible with the less formal and unstructured information needs, and too focused on strict rationality”.

Simple tools have the advantages of providing room for interaction (the user can clearly see the impact of varying input parameters and adjust accordingly), and allowing for professional interpretation and discussion of results (also those that would be intermediate and thus invisible in complex tools). Simple tools can be “manually” combined according to the needs of the users and the context they operate within, and the “space” between the tools allows the users more freedom to incorporate informal and unstructured knowledge, as well as using other (also non-technical and non-quantitative) tools such as sketching, interviewing, negotiation techniques, etc. These advantages are especially relevant when it comes to SCMs, which need to deliver multifunctionality, and thus require interdisciplinary collaboration and co-design processes (Fenner, 2017; Hansen et al., 2019).

All in all, simple tools give more “power” to the user, which, I believe, is to be preferred over giving power to calculation machines. But this, of course, is a subjective view, and thus by definition remains open to debate. In the complex world that we live in, and the variety of purposes and contexts that SCMs are to be implemented within, there is room for many different types of tools, also complex ones (as argued by many others, e.g. Guswa et al., 2014).

6 Conclusions

The overall objective of this PhD-project was to develop quantitative tools to assist different professionals in planning and designing nature based stormwater control measures (SCMs). Together with different partners I developed three different tools and one methodology. The first tool is a further development of the 3PA which adds a quantitative dimension to the definition of the three domains. The second tool is a set of Characteristic Rain Events (CREs) which provide tangible quantitative descriptions of the types of rainfall that SCMs should be designed to make visible in order to provide day-to-day aesthetic value. The methodology can be used for structuring detailed modelling studies according to the Three Point Approach (3PA). The third tool, SCM-potential, suggests a new method for quickly calculating SCM impact on key hydrological indicators, designed to give professionals interactive feedback on their site design choices. Below I will describe how these tools and methodology address the research questions of this project.

A literature review of existing tools showed that there is virtually a myriad of tools out there, some of which are quite similar while others are very different from each other. In order to create some order we proposed categorizing them according to what type of questions they could assist in answering: "how much" (water, pollution, etc. can be managed via SCMs), "where" (to situate SCMs) and "which" (SCM is the best) – or any combination hereof. Other variations among the tools include what degree of complexity they include in their processing, what degree of expertise they require from the user, what type of professional background of the user are they designed for, whether they are most useful for making overall planning strategies or for designing specific solutions, what kind of existing sewer system they fit with (combined or separate), what legal framework they are suited for, and much more. In conclusion, although there are many tools out there already, the variability in the demands that shape them also entails that there is ample room for more tools.

The tools we developed demonstrate different ways of "operationalizing" the 3PA. By computing a rainfall depth that can be considered representative of the upper boundary of each domain, we quantified the 3PA and turned it into a new, still very simple tool, yet more tangible and widely applicable than the original. The methodology for structuring state-of-the-art distributed modelling studies suggested summarizing outputs into a single quantitative indicator per domain. In the SCM-potential tool we used the 3PA as a framing for one of the two key indicators the tool calculates.

One of the ideas embedded in the 3PA is the vital role of domain A, the domain of day-to-day values. This domain is often neglected, by engineers as well as designers, and our tools demonstrate different ways of highlighting it. In our quantification of the 3PA we added a second vertical axis that notes each domain’s share of the annual rainfall, which shows that in Denmark, domain A includes 75% of the annual rainfall. This fact seems to be an eye-opener for many, educating professionals about the potential hidden in addressing this domain. The tool Characteristic Rain Events (CRE) was developed specifically to draw attention to the aesthetic performance of SCMs during times where there is only little water in them, which is the bulk of the time. The CREs can be used as single numbers (rainfall depth), graphs (of rainfall intensity over time) or as input (to a hydrological model of an SCM), to assist the designer in assessing how visible does rainwater from frequent rains become in the SCM. In the SCM-potential tool, we included as key indicator how a given SCM design will impact the annual water balance of the catchment, thus drawing attention to the potential SCMs have to improve sustainability and liveability, the values that dominate in domain A.

Throughout the tools developed emerges a methodological approach to simplifying complex hydrological processes through (pre-) processing of long time series. For the quantified 3PA and the CREs this is done through analysis of rainfall records. For the 3PA framework for distributed modelling studies and for the SCM-potential tool, this is done through analysis of hydrological simulation output time series. These simplifications are made based on 1) understanding of the hydrological processes and which parameters are most influential; and 2) strategic decisions regarding what is most essential to know in the use-context of the tool. For example, the quantified 3PA shows rainfall depths aggregated over approximately 24 hours, which is essential information for sizing retention-based SCMs; it omits rainfall intensities, which would be paramount for sizing conveyance measures (which is not the intended use-context of the tool). The SCM-potential calculator requires the user to specify the infiltration rate of the native soil because this is the most influential parameter for the impact of bioretention units (next to the area-ratio between the units and their catchments); it omits details such as the berm height of the units because they are much less influential and should therefore not be bothered with in the initial design stages.

7 Perspectives

There is still much to be done regarding development of tools that can effectively support professionals in their work with planning and designing SCMs. Fortunately, we have received a grant that will enable us to develop the SCM-potential tool to market in the next couple of years. The next step in that direction could be to develop a plug-in tool that enables hydrological simulations directly in the software packages that architects use, in order to support also the later and more detailed design stages. There is also still a need to improve the tools used by engineers, such as MU and SWMM, with regards to the representation they enable of SCMs.

Yet there is also a world outside the computer, although one can easily forget this when working at a scientific institute respected for its modelling capabilities. Unfortunately, it seems that there are more modelling studies of SCM impact than field studies. I am afraid that this has more to do with the costs of desktop studies versus the costs of field studies than any analysis showing that we have more need for modelling studies. I see a vast need for more field studies of the impacts of SCMs, both on smaller and larger scales, to help us better understand their potential and limitations, and to improve the reliability of our models.

More observations of SCM impact in the real world is both useful in itself and useful for improving our models, yet no matter how many observations we make there will always remain a great deal of uncertainty in our model predictions. Green stormwater infrastructure will inevitably include natural variability in e.g. soil media, which makes it harder to design it to be “fail-safe” compared with grey infrastructure. If we want to see a wider adoption of nature based SCMs we also need to address the institutional barriers that favour the more easily-quantifiable grey measures, and develop new design paradigms that acknowledge the strengths of the multifunctional solutions.

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In this online version of the thesis, **papers I-V** are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from.

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The Department of Environmental Engineering (DTU Environment) conducts science-based engineering research within five sections: Air, Land and Water Resources, Urban Water Systems, Water Technology, Residual Resource Engineering, Environmental Fate and Effect of Chemicals. The department dates back to 1865, where Ludvig August Colding gave the first lecture on sanitary engineering as response to the cholera epidemics in Copenhagen in the late 1800s.

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