Technical University of Denmark

Urban drainage design and climate change adaptation decision making

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Publication date:
2012

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Zhou, Q., Arnbjerg-Nielsen, K., Mikkelsen, P. S., Nielsen, S. B., & Halsnæs, K. (2012). Urban drainage design and climate change adaptation decision making. Kgs. Lyngby: DTU Environment.

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PhD Thesis
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Printed by: Vester Kopi
Virum, October 2012

Cover: Torben Dolin

ISBN: 978-87-92654-80-9

Preface

The work presented in this PhD thesis, entitled 'Urban drainage design and climate change adaptation decision making', was carried out at the Department of Environmental Engineering (DTU Environment), Technical University of Denmark. The work was conducted under the supervision of Associate Professor Karsten Arnbjerg-Nielsen, with Associate Professor Peter Steen Mikkelsen, Associate Professor Susanne Balslev Nielsen (DTU Management) and Head of Climate DTU Kirsten Halsnæs (DTU Management) as co-supervisors. The PhD project was completed in the period from May 2009 to April 2012 and funded by DTU Climate Center.

The content of the thesis is based on five scientific papers submitted to peer-reviewed journals or conferences. The thesis comprises a summary of the background, objectives, methodologies and findings of the PhD project as well as the scientific papers listed at the end. The papers are referred in the text by their associated roman numbers, e.g. Paper I.

I. **Zhou, Q.**, Mikkelsen, P. S., Halsnæs, K., Arnbjerg-Nielsen, K. (2012). *Framework for economic pluvial flood risk assessment considering climate change effects and adaptation benefits*. Journal of Hydrology, 414–415(0), 539-549.

II. **Zhou, Q.**, Halsnæs, K., Arnbjerg-Nielsen, K. (2012). *Economic assessment of climate adaptation options for urban drainage design in Odense, Denmark*. Water Science and Technology, 66(8), 1812-1820.

III. **Zhou, Q.**, Panduro, T. E., Thorsen, B. J., Arnbjerg-Nielsen, K. *Verification of flood damage modeling using insurance data*. The 9th International Conference on Urban Drainage Modelling, Belgrade, Serbia, 4 -7 September 2012.

IV. **Zhou, Q.**, Arnbjerg-Nielsen, K. *Uncertainty assessment of climate change adaptation options using an economic pluvial flood risk framework*. Submitted manuscript.

V. **Zhou, Q.**, Panduro, T. E., Thorsen, B. J., Arnbjerg-Nielsen, K. *Adaption to extreme rainfall with open urban drainage system – An integrated hydrological cost benefit analysis*. Submitted manuscript.

The following articles were prepared during the PhD study, however, they are not included as part of the thesis:

- Zhou, Q., Quitzau, M., Hoffmann, B., & Arnbjerg-Nielsen, K. *Towards adaptive urban water management: up-scaling niche experiments*. Submitted manuscript.

- Zhou, Q., Arnbjerg-Nielsen, K. *Uncertainty assessment of climate change adaptation options in urban flash floods.* WSUD 2012 - 7th International Conference on Water Sensitive Urban Design: Building the Water Sensitive Community, Final Program and Abstract Book.

- Zhou, Q., Arnbjerg-Nielsen, K (2011). *A risk-based evaluation tool for feasible urban drainage design under influence of climate change*. Proceedings abstract, cities of the Future: Sustainable urban planning and water management, Stockholm, Sweden.

- Zhou, Q., Arnbjerg-Nielsen, K., Mikkelsen, P. S., Halsnæs, K., Nielsen, S.B. *Design practice for urban drainage incorporating climate change impacts.* In Proceedings of the 6th Study Conference on *BALTEX*, Miêdzyzdroje, Poland, 14-18 June, 2010.

The papers **I-V** are included in the printed version of the thesis but not in the www-version.
Copies of the papers can be obtained from the
Library at DTU Environment.
Department of Environmental Engineering
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Acknowledgements

First of all I would like to thank my supervisor Karsten Arnbjerg-Nielsen for his continual support and guidance along the PhD project. I am grateful for his professional discussions and suggestions that helped me to develop a scientific understanding of the subject. Also sincere thanks to my co-supervisors Peter Steen Mikkelsen, Kirsten Halsnæs and Susanne Balslev Nielsen for their inspirations, encouragement and valuable comments on my research work. Your contributions have been a great help to my work and encouraged me to take a more comprehensive study in the subject.

It has been a big pleasure to work with Professor Bo Jellesmark Thorsen and Toke Emil Panduro from KU Life on the extended economic framework and insurance data analysis. I am also grateful for the collaborations with Assistant Professor Maj-Britt Quitzau and Associate Professor Birgitte Hoffmann from DTU Management on the transition theory studies. Thank you all for the inspiring collaboration and it has been a great experience.

A special gratitude to Annette Brink-Kjær (VandcenterSyd) and Inge Halkjær Jensen (Aarhusvand) who have provided information and data of the two case study projects. Also appreciation to Lina Nybo Jensen (Lina Nybo ApS) for helping with the modelling challenges in the two projects.

I would also like to thank the company of my office mates and colleagues at DTU Environment. Thanks also go to Henri and Atiq for their friendship through these years. Many thanks to dear Jin for his warm encouragement and support when moments were difficult. Finally I would like to express my love and appreciation to my family for their unconditional support of all my endeavours.

Summary

Since the middle of the 19th century urban drainage has been a vital infrastructure in cities. Traditionally, urban drainage has been used as a convenient cleaning mechanism for public hygiene and an efficient conveyance facility to tackle floods for life and assets protection. From the early 20th century, the design objectives of urban drainage systems also include elements such as environmental protection and amenity values. Among the objectives, flood protection has received much attention in recent years as a result of increasing flood hazards and risks due to climate change impacts. Although mitigation steps have been taken in attempts to reduce global warming, adaptation is highly advocated to supplement mitigation to cope with the unavoidable adverse impacts of flooding on vulnerable assets.

The emphasis of this PhD thesis is flood protection in the context of pluvial flooding by investigating new principles and approaches for assessment of urban drainage adaptation measures under climate change impacts. The thesis describes a new framework for design and analysis of urban drainage that accurately assesses hazards and vulnerabilities of urban areas and quantifies the present and future risks based on projections of climate change and city development. Furthermore, this framework can be utilized to identify cost-effective measures that can reduce the overall flood risk to an acceptable level considering both costs and benefits of adaptation. The framework is mainly based on a utilitarian approach that studies urban drainage adaptation solutions from a socio-economic point of view. The methodologies involve the state-of-the-art flood inundation modelling, risk assessment tools, socio-economic analysis tools, city planning, and uncertainty analysis.

The thesis has explored several limitations of the current design practice of urban drainage. To further supplement and develop the common practice, a systemic and integrated framework is proposed by incorporating three research areas: (i) risk-based economic approaches for assessment of climate adaptation design, (ii) uncertainty analysis of climate adaptation assessment and (iii) reframing the assessment approaches by incorporating additional benefits and costs of adaptation alternatives.

To strategically provide a functional performance of urban drainage systems, a risk-based economic approach is developed to take into account the impacts of all probable floods in terms of their probabilities and consequences (e.g. extents of floods, costing of damage). It is found that this approach contributes to a better understanding of the contributions of different return periods/flood events to the overall risk under both current and future climatic conditions and therefore can be used as guidance for further adaptation actions (e.g. formulation of an appropriate service level). Furthermore, the risk-based economic approach enables an assessment and comparison of the expected benefits (due to saved flood damage) and corresponding costs of different adaptation measures. This gives more detailed insights into the pros and cons of different adaptation options, thus helping to optimize the efficiency and performance of urban drainage adaptation design.

The thesis investigates impacts of uncertainties associated with not only the hydrological conditions (e.g. design intensities, climate change impacts), but also the present and future vulnerability conditions (e.g. impacts on assets). This enables a complete assessment of effects of various uncertainties in the climate change assessment process. Furthermore, in the study, two types of uncertainties are distinguished: 1) the overall uncertainty of an individual adaptation scenario, which may influence the choice of action; and 2) the marginal uncertainty between adaptation alternatives in order for a direct comparison of their efficiency once a decision of action is taken. Based on assessments of the two types of uncertainties, it is found that although climate change adaptation assessment is often associated with large uncertainties, it is still possible to identify robust adaptation options based on calculated marginal uncertainties. This is because that the uncertainties related to costing of floods and magnitude of climate impacts will be levelled out when comparing adaptation alternatives. In addition, a sensitivity analysis is also incorporated in the framework to assess the relative contribution of inherent uncertainties in the assessment. This allows an identification of critical/important uncertainties that matter for decision making and also provides a guide for further efforts to improve decision making in relation to climate change adaptation.

Traditionally, assessment of climate change adaptation is based on conventional engineering solutions, meaning that only response impacts in the context of hydrological extremes are considered while the added intangible values (e.g.

recreational amenities due to a nice blue-green neighbourhood) of adaptation options are often ignored or underestimated. In order to facilitate the development and implementation of water sensitive urban design concepts climate change adaptation tools must take into account the additional benefits of using these concepts. This thesis develops a reframed design framework to account for such intangible goods/values of adaptation options. This serves as a valuable basis for evaluating the benefits of provision of positive environmental values and the preservation of water resources. It is found that neglecting intangible values in climate adaptation assessment can easily bias the decision making; the reframed approach hence provide an important tool for assessment of additional benefits and costs of such innovative solutions.

The thesis points towards an integrated framework for urban drainage adaptation design considering climate change effects and adaptation benefits and costs. The case studies show how the proposed framework can be utilized to manage the anticipated climate change risks in a cost-effective way under different circumstances. The introduced framework provides an important supplement or replacement of current design practices under influence of climate change.

Dansk sammenfatning

Siden midten af det 19. århundrede har kloakering af bebyggede områder været en vital del af byers infrastruktur. Kloakeringen skete for at forbedre hygiejnen og sikrede samtidigt mod materielle skader ved at mindske risikoen for oversvømmelser. Siden starten af det 20. århundrede har fokus ved design af kloaksystemer imidlertid flyttet sig til i højere og højere grad også at tage beskytte miljøet og udnytte vandet til rekreative formål. I de seneste år har beskyttelse mod oversvømmelser fået stor bevågenhed på grund af den stadig større risiko for oversvømmelser som en konsekvens af et ændret klima. Som et supplement til de tiltag der allerede er taget for at reducere den globale opvarmning, er det derfor stadig fordelagtig at tilpasse sig det nye klima, og dermed imødegå de uundgåelige skadevirkninger fra oversvømmelser.

Hovedvægten i denne PhD-afhandling er lagt på at udvikle nye principper i forbindelse med beskyttelse mod oversvømmelse skabt af ekstreme regnhændelser, samt at identificere nye tilgange til at vurdere de foranstaltninger, der er nødvendige for at tilpasse os til et ændret klima. Afhandlingen er hovedsagelig tænkt som en ny metodik/design praksis for kloakingeniører og vandforsyningsselskaber. Arbejdet i denne afhandling er derfor hovedsagelig udført ud fra en nyttebaseret tilgang. Den ser på ændringerne i oversvømmelsesrisiciene under et ændret klima, samt på den tekniske og økonomiske gennemførlighed af kloaktilpasningsløsninger ud fra et økonomisk perspektiv. Metodikken benytter state-of-the-art metoder indenfor områderne risikoanalyse, samfundsøkonomi, byplanlægning og usikkerhedsanalyse.

I afhandlingen har vi identificeret flere begrænsninger i den nuværende dimensioneringspraksis for kloakker. Som et supplement til og fremtidig udvikling af den normale praksis, har vi udviklet en systematisk og integreret model som består af følgende komponenter: (1) En risikobaseret økonomisk tilgang til at vurdere effekten af klimatilpasningstiltag, (2) En usikkerhedsanalyse i forbindelse med vurderinger af tiltag til klimatilpasning og (3) En ændret analyseramme for dimensionering af kloaksystemer, der også eksplicit inkluderer vands rekreative værdier.

Der er udviklet en risiko- og økonomi- baseret metode til analyse af afvanding af byer, der medtager effekten af alle tænkelige oversvømmelser, hver vægtet med hensyn til deres respektive sandsynlighed og konsekvens. Denne metode har vist sig at give en væsentlig forbedret forståelse af, hvordan nuværende og forventede fremtidige hyppigheder af oversvømmelser bidrager til den samlede risiko for oversvømmelser. Metoden beregner oversvømmelsesrisikoen både under nuværende og forventede fremtidige klimatiske forhold, og kan benyttes som beslutningsstøtte ved vurdering af mulige tilpasningstiltag, herunder formulering af servicemål for oversvømmelser samt hvordan disse bedst kan sikres opfyldt. Denne kombinerede risikoøkonomiske tilgangsvinkel gør det desuden muligt at vurdere og sammenligne forskellige tilpasningstiltag ud fra deres respektive fordele og tilhørende omkostninger. Igennem disse sammenligninger bliver det muligt at opnå en dybere indsigt i fordele og ulemper ved forskellige tilpasningsscenarier og dermed optimere den samlede håndtering af afvanding af byer.

Afhandlingen evaluerer effekten af usikkerheder, ikke kun i forbindelse med afstrømningen og deraf følgende farer for oversvømmelse, men også i de nuværende og fremtidige sårbarhedsforhold. Dette gør det muligt at lave en fuld evaluering af de forskellige usikkerhedsbidrag i forbindelse med vurderingen af klimaændringerne og egnede tilpasningstiltag. Der skelnes mellem to typer af usikkerheder: (1) Usikkerheden på hvorvidt det kan anbefales at lave tilpasningstiltag, og (2) Usikkerheden ved sammenligning mellem forskellige tilpasningsscenarier. Ved anvendelse af metoden på et case studie er det fundet, at det er forbundet med store usikkerheder at vurdere, hvorvidt det er optimalt at lave tilpasningstiltag, mens det er muligt at lave en robust udpegning af, hvilket tiltag, der er optimalt blandt de undersøgte. Årsagen hertil er, at usikkerhederne i forbindelse med prissætning af skader givet en oversvømmelse er store. Derudover er der udført en følsomhedsanalyse for at bedømme de relative bidrag fra usikkerhedsmomenterne i vurderingen. Dette gøre det muligt at identificere usikkerheder som er vigtige i beslutningsprocessen og hvor der i fremtiden skal lægges en indsats for at forbedre beslutningerne.

Traditionelt set, har vurderingen af klimaændringstilpasninger været baseret på konventionelle ingeniørbetragtninger. I den henseende, at kun de materielle konsekvenser af hydrologiske ekstremer er inddraget i vurderingerne, imens de immaterielle værdier ofte er undervurderet eller direkte ignoreret. På grund af den stigende interesse for at anvende vand rekreativt i byer i såkaldte Water Sensitive Urban Designs er det vigtigt at udvikle redskaber som kan medtage immaterielle værdier ved dimensionering og analyse af afstrømning af vand i byer. Denne PhD-afhandling beskriver en nyt koncept som inkluderer disse immaterielle værdier i vurderingen af klimatilpasninger, så disse immaterielle værdier eksplicit inddrages i beslutningsprocessen. Den fremførte model er et vigtigt redskab til at vurdere de ekstra fordele og ulemper for nye innovative løsninger på tværs af traditionelle faggrænser.

Denne afhandling er et skridt på vejen mod en integreret designmodel for tilpasning af kloaksystemer til fremtidige klimaændringer, som medtager fordele og omkostninger ved tilpasningerne. Case studierne viser hvordan den introducerede model kan benyttes til at håndtere de forventede risici for klimaforandringerne på en omkostningseffektiv måde. Den introducerede model er et vigtigt supplement og nødvendig udbygning for nuværende designmetoder i et fremtidig omskifteligt klima.

Contents

1. Introduction

1.1 Floods and Urban drainage

Over the last few decades, Europe has experienced an increasing number of floods. Just between 1998 and 2004 Europe suffered over 100 major floods, which caused about 700 deaths and at least 25 billion EUR of losses in insured costs (European Commission, 2012). Nowadays there are still unpleasant memories of several catastrophic floods in Europe, e.g. the October 2000 floods in Italy, the August 2002 floods in Poland and Germany, and the June and July 2007 floods in England (Floodsite, 2009). Among these, many disasters are caused by pluvial floods when runoff from an extreme rainfall exceeds the capacity of the drainage system and thus the excess runoff cannot be conveyed. Such a type of flooding is one of the most significant natural hazards in urban areas and often results in enormous damage due to the high concentration of people and socio-economic values in cities. Here is a Danish example: The greater Copenhagen was hit by two major urban pluvial floods in 2010 and 2011. The heavy rains have caused severe traffic delays, and large damage to properties and infrastructures in cities. It was reported that the insured damage alone has reached 600 million EUR in 2011 and the indirect damage costs were about 800 million EUR (Environment Solutions, 2011).

Urban drainage is a vital city infrastructure to cope with floods by conveying water away from urban areas. To minimize the flood impacts, the main principle is to carry water away from the urbanized areas as quickly and completely as possible (Chocat et al., 2004; Stahre, 2006). Traditionally, drainage systems mainly consist of pipe networks with underground structures. Such systems are very costly to build; therefore a service level is often proposed to indicate an acceptable frequency of system overloading, thus achieving a balance between the capital investments and the risk level of flooding. This means even with a functioning drainage system, the design capacity is still limited to cope with the extreme rainfalls and floods are expected to occur when the system gets overloaded.

1.2 Problem framing

1.2.1 Climate change impacts and adaptation

It is commonly recognized that climate change will have significant impacts on the water cycle and precipitation patterns (Solomon et al., 2007; van der Linden and Mitchell, 2009). In some regions such changes are expected to entail an increase in the frequency and intensity of precipitation extremes, thus leading to increased risk of flooding (Mailhot and Duchesne, 2010; Parry et al., 2007). In Denmark, several studies indicate that a 20%-40% increase in design intensity is expected over the next 100 years based on 1-hour extreme estimation (Arnbjerg-Nielsen, 2012; Larsen et al., 2009; Madsen et al., 2009). With the anticipated changes, the drainage system built in the past and today cannot meet the desired capacity in the future; as a result there will be a substantial increase in flood damage due to more frequent overloading of the drainage system in the future.

Although mitigation has been adopted worldwide to tackle climate change impacts, adaptation is necessary to cope with the unavoidable adverse impacts on vulnerable areas (European Commission, 2009; Walsh et al., 2011). Over time the service level of drainage will alter due to climate change impacts; design of future drainage systems will have to incorporate the increased frequency and intensity of rainfall to maintain the acceptable risk level of flooding. There is an urgent need to revisit the established design practices of urban drainage and develop a more strategic approach incorporating the anticipated climate change impacts for the actual design. If designed properly, adaptation measures can be well integrated in the city functions, and hence, not only lessening the potential flood damage to society, but also enhancing synergy for sustainable development and bringing clear economic benefits to people, the economy and the environment (European Commission, 2009; Hall et al., 2009).

A number of actions have been initiated in attempts to adapt to climate change impacts, however, mainly for fluvial and costal floods at large scales (Dawson et al., 2009; Hall et al., 2006; Hallegatte et al., 2011; Jonkman et al., 2008; Morita, 2008). Adaption to pluvial flooding remains a challenging task for most urban areas (Ashley et al., 2007). The challenges will be explored from the following three perspectives:

- ***Complexity of urban drainage network.*** Urban drainage system often consists of a large number of underground structures, such as pipes, manholes, pumps and basins. These interconnected structures often exhibit complex non-linear dynamics, which makes it difficult to optimize the technical performance of the drainage system and the costs and benefits in relation to adaptation (Vojinovic et al., 2012).
- ***Complexity of urban context***. When assessing flood risks, urban context is often more complex in terms of the temporal and spatial distributions of population, infrastructure and socio-economic activities. This requires a more detailed and comprehensive assessment in terms of the damages and costs required for adaptation.
- ***Complexity of adaptation measures***. Last but not least, in comparison with large scale adaptation for pluvial and fluvial flooding, there are a large number of small-scale and decentralized methods for adaptation in cities, which requires more knowledge and skills to model and estimate their impacts (Elliott and Trowsdale, 2007)

1.2.2 Limitations of current design practices

To in line with the European standard EN 752 for drainage systems (CEN, 1996; CEN, 1997), a new design practice for urban drainage was established in Denmark in 2005 (Harremoës et al., 2005). The common design practice is built upon three key elements:

- *Formulation of functional requirement - a minimum service level*

The design practice has focused on assessing appropriate minimum service levels at the municipality scale (Arnbjerg-Nielsen and Mikkelsen, 2009; Harremoës et al., 2005). Such a design practice is formulated primarily based on a probabilistic approach, which considers only one service level/flood frequency for a large area/catchment to avoid functional failure instead of taking into account impacts of all probable floods. What is more, categorizations of the landuse and recommended service levels are very crude, which fails to account for the complexity of practical applications. Especially, city areas are highly complex and the present social and economic activities differ significantly from area to area. Such a uniform service level may fail to optimize the efficiency of investments and exhibit limited capacity for risk reduction.

- *Recommendation of design methodologies*

The practice introduced three computational methods ranging from rational method to dynamic analysis of historical rain series, see Table 1-1 (Harremoës et al., 2005). All three methods are used to comply with the functional requirement of drainage systems in relation to service level, rather than economic optimization of investments. There is a lack of advanced inundation models and socio-economic tools to assess the actual flood consequences and the associated costs and benefits in the design. Therefore, the design of the system may be robust in terms of capacity dimensioning, however, not economically sensitive.

Table 1-1: A 3-level calculation method recommended in the curernt danish design practice

Level	Method	Rain data	Criterion
1	Rational method	IDF curve	Full flow pipes
2	Dynamic model	CDS rain	Service level
3	Dynamic model	Historical rain	Service level

- *Handling of present and future uncertainties*

In the design practice, safety factors are applied to take into account the present and future uncertainties, however, mainly in the context of extreme hydrologic loadings, e.g. rainfall and runoff. In other words, uncertainties associated with e.g. impacts on assets and costing of damage have not been included in the current practice. It is therefore of high interest to adopt an integrated analysis accounting for uncertainties of response impacts of both hazard and vulnerability conditions.

The impacts on extreme precipitations due to climate change have been addressed in the design practice, however, without further elaborations on how to adapt urban drainage systems to the anticipated changes. Although there are some instant adaptation responses to the increasing flood risks in Denmark (e.g. (Arnbjerg-Nielsen and Fleischer, 2009), the concepts have not yet been developed into a framework that can be used as a guideline for actual assessment of climate adaptation design. This indicates a need to establish and evaluate new principles of urban drainage adaptation under climate change.

1.2.3 Decision making on climate change adaptation - in need of new design methodologies

Although the current design guidelines for urban drainage in many cases provide an adequate design, there is a need for further development. Three shifts are proposed to supplement and further develop engineering practice:

- *Probabilistic design → Risk-based design*

A risk-based design is proposed to reduce overall flood risk by accounting for all floods in terms of their impacts and probabilities (Dawson et al., 2008; de Moel et al., 2009; Petrow et al., 2006; van Duivendijk, 1999). In the approach, state-of-the-art inundation modelling is used to supplement the three computational methods to assess the corresponding flood impacts when system gets overloaded. Furthermore, the risk-based design requires a combined estimation of both costs and benefits. On the one hand, urban drainage design should aim for maximizing benefits by means of reducing damage costs of flooding as much as possible. On the other hand, the drainage system is very expensive to build and maintain, which requires a proper design to best allocate the resources and money for investment. Economic tools are therefore integrated in the risk-based design to assess the efficiency of proposed options.

- *Single-value estimate → Uncertainty assessment*

Assessment of climate change adaptation should take into account uncertainties related to both present and future hazard and vulnerability conditions. However, uncertainty has often been ignored in such assessments and therefore the evaluation results are merely expressed in the form of a single-value-estimate. Decision makers often have different attitudes towards perceived flood risks (Renn, 1998; Weber et al., 2002); such single-value estimates, with limited information on uncertainty, are no longer sufficient for best decision making on climate change adaption (Beven, 2009; Walker et al., 2001; Wurbs et al., 2001). It is therefore essential to account for all uncertainties in the climate change adaptation assessment to identify robust adaptation measures (Koivumaki et al., 2010; Merz and Thieken, 2009).

- *Traditional engineering solutions → Reframing framework*

Increasingly, the sustainability of traditional urban drainage solutions are questioned due to concerns on e.g. pollutions from drainage systems, complexities and uncertainties associated with climate change impacts (Cain, 2012; Pahl-Wostl et al., 2008; Stahre, 2006; Wong and Brown, 2009). There is growing recognition of the potentials of water sensitive urban design (WSUD) to achieve better water management utilizing interconnected urban landscapes. Besides the impacts on flood risk reduction, these solutions are characterized by their potential for adding aesthetical, social and environmental values in the urban environment.

However, the current drainage design practice is grounded on the tradition of engineering solutions, indicating that the efficiency of drainage solutions is mainly assessed based on their technical and economic performance in relation to risk reduction in a hydrological context (Gafni, 2006). As a result, in most cases, the benefits of these sustainable solutions are underestimated due to a lack of appropriate economic tools to underpin their efficiency (Marsalek and Chocat, 2002; Stahre, 2006; Wong and Eadie, 2000). A reframed design approach is therefore needed in order to take into account the costs and benefits of the added values/effects from the sustainable solutions.

1.3 Objective and thesis outline

1.3.1 Objective

The objective of this thesis is to establish a systemic and integrated framework for climate change adaptation assessment. The framework focuses on how to cope with the three shifts needed in the current design practice. It is aimed to achieve practical guidelines that integrate risk assessment and management tools, climate change adaptation, socio-economic valuation tools and city planning for the actual design of urban drainage adaptation measures.

1.3.2 Thesis outline

Chapter 2 gives an introduction to urban drainage adaptation measures and design strategies. Chapter 3 illustrates an economic pluvial flood risk assessment framework for assessment of climate change adaptation measures. Chapter 4 deals with uncertainty and sensitivity analysis of the economic assessment based on the aforementioned risk-based framework. Both chapter 3 and 4 focus on climate change adaptation based on the traditional urban drainage design approaches, see Figure 1-1. Chapter 5 shows a reframed approach accounting for additional intangible values (e.g. recreational amenities) of landscape-based adaptation solutions. Chapter 6 and 7 contain the discussions and main conclusions drawn from the PhD study. Finally chapter 8 presents some recommendations for future work.

Furthermore, the thesis also contains four journal papers (Paper I, II, IV, V) and one conference paper (Paper III). The contents and relevance of the papers in relation to the thesis chapters are shown in Figure 1-1 as well.

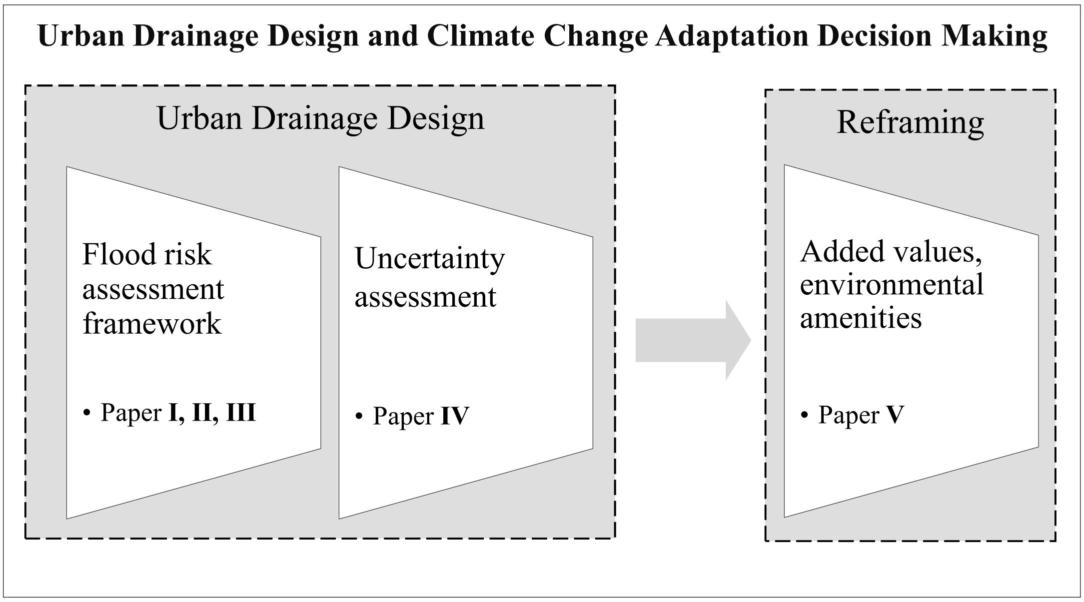

Figure 1-1: Thesis outline.

2. Managing flood risk by incorporating climate change adaptation

Climate change adaptation involves a large variety of initiatives and measures (e.g. adjustments of economic activities, human behaviour or structures of systems) to reduce the anticipated adverse consequences associated with climate change effects (Parry et al., 2007; Smith et al., 2000). In this thesis, climate change adaptation is discussed in the context of urban drainage, which involves a set of options to manage the increasing risk of flooding by tackling flood hazards and/or vulnerabilities. The efficiency of adaptation will vary depending on not only the type and form of adaptation measures, but also the choice of adaptation strategy. According to Refsgaard et al. (2012) and Smit et al. (1999), an adaptation strategy can be described in four dimensions: the intent, timing, spatial scope and temporal scope. Different formulations of adaptation strategy will lead to different impacts on flood damage, see an example in Figure 2-1. On the other hand, the choice of adaptation strategy can be influenced by e.g. associated benefits and costs of adaptation, available resources and cultural differences (Willems et al., 2012b). To formulate a strategic climate adaptation, it is important to gain knowledge on the four dimensions of the adaptation options as well as understand the corresponding impacts when different adaptation strategies are adopted.

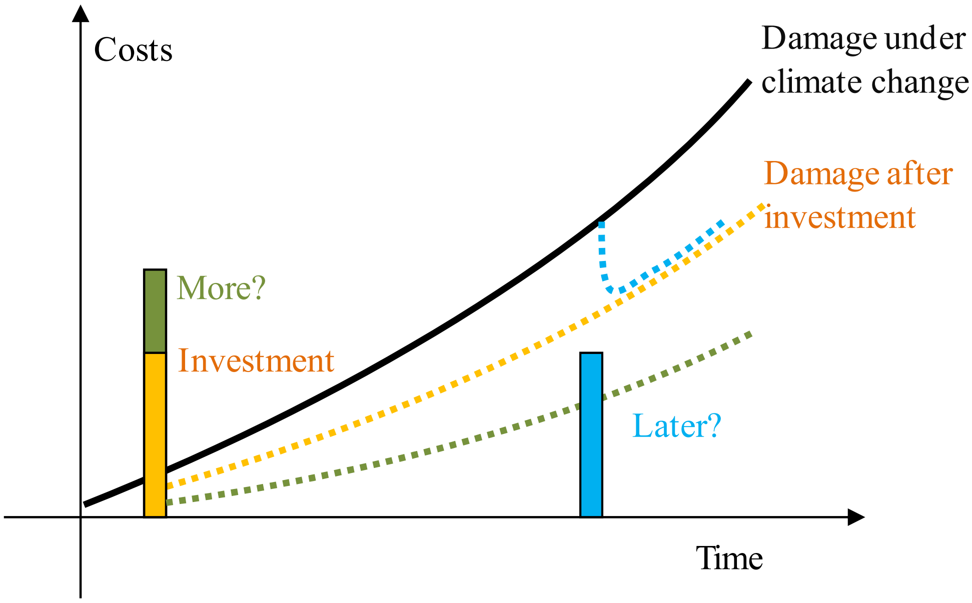

Figure 2-1: Impacts on flood damage due to different adaptation strategies. The extent of the investment and the timing of the action have an influence on the costs of flood damage, adapted from (Arnbjerg-Nielsen and Mikkelsen, 2009).

This chapter gives an overview of options for climate change adaptation. First of all, the options are discussed in terms of their capabilities in relation to risk reduction and then distinguished based on their characteristics (Kundzewicz, 2002). Next, choice of adaptation strategy is discussed based on descriptions of the four dimensions.

2.1 Adaptation options

Climate change adaptation implies a risk reduction process by means of managing hazards and/or vulnerabilities (Brooks, 2003; Hauger et al., 2006). Depending on the specific local context, flood risk can be best reduced by targeting hazards through counteracting the increase in flood frequency or extent and/or by reducing the exposure of vulnerable people or properties to hazards (Burrell et al., 2007; Floodsite, 2009). The efficiency of adaptation can vary from case to case and it is site-specific whether hazard reduction or vulnerability reduction is preferable. However, when selecting measures for adaptation, it is important to consider both hazard and vulnerability characteristics to allow for best solutions.

There is a wide range of measures to reduce risk in different manners, which can be categorized into three groups in terms of their impacts on the hydrological runoff process (Floodsite, 2009; Stahre, 2006), see Figure 2-2: 1) Upstream control measures, aimed to detain, attenuate or reduce the generation of excess water runoffs in the upstream of the drainage system. Examples are green roof, ponds and local infiltration; 2) 'In system' control measures, include different kinds of measures to prevent or reduce flood impacts on vulnerable receptors, such as topographic change, flood defence, land use change, individual assets protection; 3) Downstream control measures, aimed at enhancing the conveyance capacity of drainage systems to transport water away faster in the downstream. Examples are pipe enlargement, road management, pumps and relief channels. A better understanding of the individual performance of each group of measure is the basis for promoting integrated and coordinated adaptation solutions.

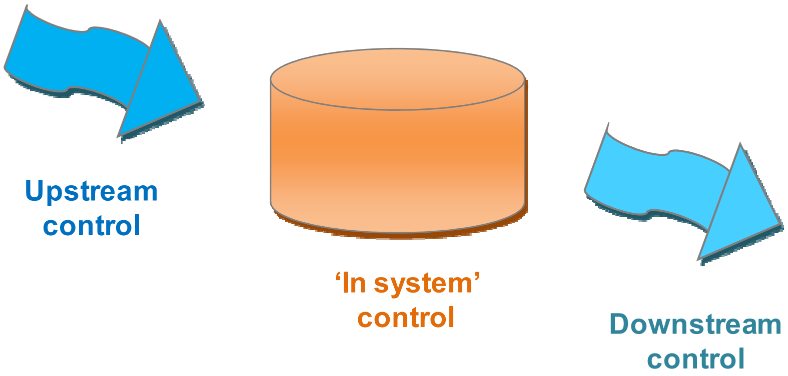

Figure 2-2: Categorization of adaptation options based on their impacts on the hydrological runoff process.

Moreover, responses to climate change impacts can be structural (hard) and non-structural (soft). Traditional urban drainage systems consist of mainly structural measures, such as pipes, diversions, and underground basins. These types of measures often have strong physical interference in the environment (Floodsite, 2009; Kundzewicz, 2002). Non-structural measures, in contrast, are intended to influence the behaviour and attitude of stakeholders to reduce flood risk, through knowledge, practice and agreement (Dawson et al., 2011; Floodsite, 2009; Kundzewicz, 2002; Taylor and Wong, 2002). Examples of non-structural measures are flood proofing, flood forecasting and warning, and economic instruments (e.g. insurance). The definitions of the structural and non-structural measures are easy to understand; however, in practice it is difficult to distinguish and separate the two measures (Floodsite, 2009). Climate change adaptation strategies will most likely contain a mix of the structural and non-structural measures.

In this PhD study the aim is not to investigate a broad range of adaptation options, but to analyse a few adaptation measures applied in the case studies in response to climate change impacts. Figure 2-3 illustrates the classification of these solutions based on their characteristics and roles in risk reduction.

1) ***Infiltration*** *(mainly upstream control)*, to mitigate and slow down the water runoffs through local infiltration trenches. The implementation of infiltration demands a mix of structural and non-structural measures to reduce flood hazards through both engineering structures and policy regulations.

2) ***Recreational open basin*** *(mainly upstream and 'in system' control)*, a structural measure mainly aimed at reducing flood hazards by temporary detention of stormwater. Whereas, such a measure often incorporates urban landscape transformation to provide recreational services to public. In many cases, it is necessary to change land use in the local context to provide more space for water storage, such as removing vulnerable houses from local depressions (See examples from Paper V). This indicates a change in flood vulnerabilities due to implementation of the solution.

3) ***Individual assets protection*** *('in system' control),* to reduce exposure of vulnerable properties to potential hazards by means of small-scale structural and non-structural measures, including the removal of houses in high flood risk zones, installation of anti-flood pump in basements and construction of flood proofing walls for vulnerable properties.

4) ***Pipe enlargement*** *(downstream control)*, a traditional urban drainage solution to increase the transportation capacity of excess runoff volume. It is a structural measure aimed at managing hazard characteristics to reduce flood risk.

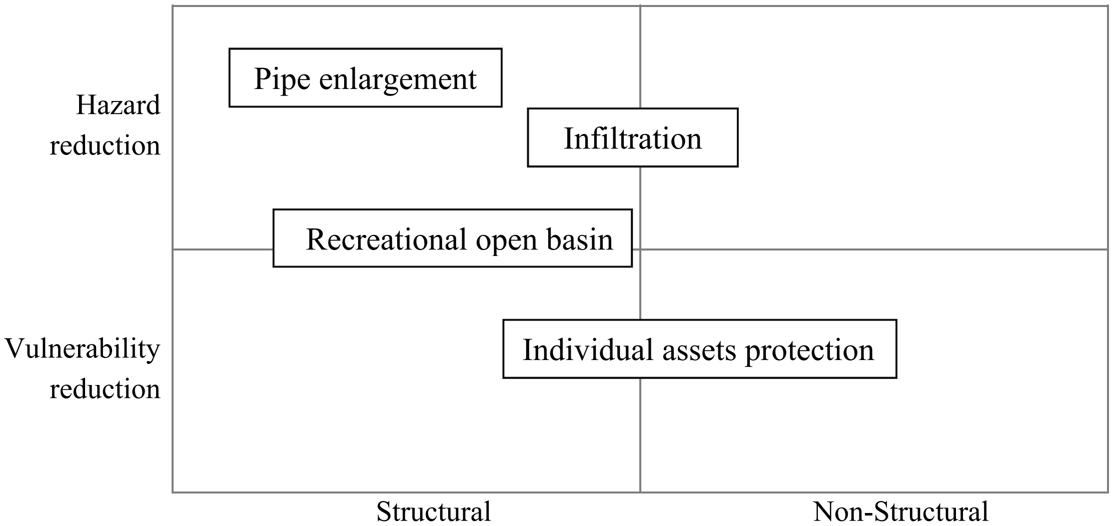

Figure 2-3: Classification of the applied adaptation solutions based on their characteristics and roles in risk reduction.

2.2 Adaptation strategies

Adaptation options can be differentiated according to the intent, the timing of the action, and their spatial and temporal scopes, see Figure 2-4. Meanwhile, adaptation actions can be undertaken by different actors/agents, such as governments, communities, private actors, industries and individuals. The attributes of adaptation depend to a great extent on the involved actors. Therefore, any analysis of adaptation requires an identification of the key stakeholders as well as an understanding of their roles in the decision making process.

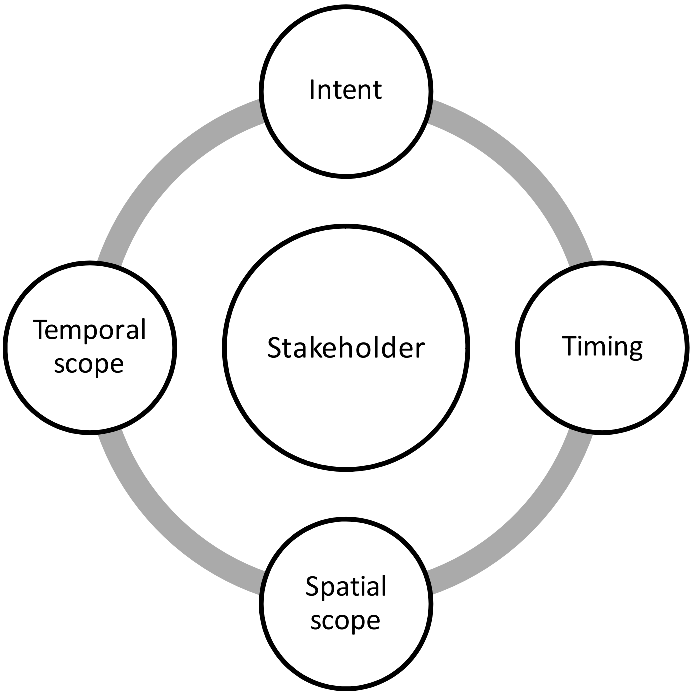

Figure 2-4: Attributes for differentiating adaptation options.

Intent: Adaptation to climate change can be spontaneous or planned (Smit et al., 1999; Smith et al., 2000). Spontaneous adaptation implies an immediate and perhaps even unconscious response taken by vulnerable individuals to deal with the climate change impacts (Arnbjerg-Nielsen and Fleischer, 2009; Parry et al., 2007). Such spontaneous actions, in general, consist of short-to-medium-term reactive measures at a local scale (Refsgaard et al., 2012). Planned adaptation is a result of deliberate policy action progressed from a top-down approach. In most cases, the planned adaptation is more cost-effective from a long-term perspective (Parry et al., 2007; Smit et al., 1999).

Timing: Adaptation can be reactive or anticipatory according to the timing of the action (Smit et al., 1999). Anticipatory and reactive adaptation implies actions taken place before and after impacts of climate change are observed, respectively (Levina and Tirpak, 2006). Anticipatory adaptation is often planned while reactive adaptation can occur spontaneously or be planned. In most circumstances, anticipatory planned adaptations will incur lower long-term costs and be more effective than reactive adaptations. In many cases, anticipatory adaptation is desired to act on the potential serve impacts of climate change based on the precautionary principle (EEA, 2001; Gregersen and Arnbjerg-Nielsen, 2012).

Temporal and spatial scope: Adaptation impacts can be wide or localized with respect to spatial scope; the temporal scale of effects of adaptation measures can be short or long (Smit et al., 1999). In adaptation, it is often desired to have actions with longer and wider effects to cope with climate change. Equally important, the adaptation should be flexible and resilient in terms of both temporal and spatial scope.

To achieve a better understanding of the impacts of the four applied adaptation options in the case studies, we compare them with a business-as-usual (BAU) scenario and summarize their impacts based on the aforementioned attributes/dimensions in Table 2-1. Traditionally, municipalities and /or utility companies take the lead responsibility for operating and maintaining urban drainage systems. Actions taken by municipalities are usually anticipatorily planned for a long time period. The spatial scope of the actions is often within the municipality. The BAU scenario indicates a situation where no adaptation activity is initiated; however, regular drainage planning remains the same. Pipe enhancement implies an action by utility companies and is therefore more line with the BAU. This type of option usually has a long-term impact and a large spatial scope. Infiltration requires actions at the household level and therefore involves individual property owners in the adaptation. The change in roles consequently alters the attributes of the option; the action normally has a short- or medium-term impact. Recreational open basin indicates an action between the pipe enlargement and infiltration. The action is mainly taken at the utility level; however, individual stakeholders are involved when actions conflict with their interests. The spatial scopes of infiltration and recreational open basin may differ from case to case; however, widespread effects are needed for both measures if an effective risk reduction is desired. Individual assets protection needs to engage substantial individual actions at the household level to cope with climate change. The temporal and spatial scope of the action is often small and the efficiency of the action is very dependent on local participation.

Table 2-1: Overview of applied adaptation measures in terms of attributes.

	Intent	**Timing**	**Temporal scope**	**Spatial scope**	**Actors involved**
BAU	Planned	Anticipatory	Long	Municipal	Utility
Pipe enlargement	Planned	Anticipatory	Long	Widespread	Utility
Infiltration	Planned	Anticipatory	Short-medium	Widespread & localized	Property owners
Recreational open basin	Planned	Anticipatory	Short-medium	Widespread & localized	Utility/ Individual stakeholders
Individual assets protection	Planned & Spontaneous	Anticipatory & reactive	Short	Localized	Property owners

3. A risk-based economic framework for climate change adaptation assessment

This chapter illustrates a framework for economic pluvial flood risk assessment considering climate change impacts and adaptation costs and benefits. The framework is an extension of the risk framework laid out in the EU Flood Risks Directive (European Commission, 2007). The framework consists of a flood risk framework and a socio-economic framework for assessment of costs and benefits of adaptation measures. The chapter is based on paper I and paper II.

3.1 Assessment of flood risk

3.1.1 Flood risk assessment framework

In the literature risk has been defined in a number of ways, however, somewhat in a similar manner (Brooks, 2003; Crichton, 1999; Floodsite, 2009; Granger et al., 1999; Hauger et al., 2006; Helm, 1996; Samuels, 2006). In the engineering community, flood risk is traditionally defined as a product of occurrence probability of an event and its consequence (Hauger et al., 2006; Helm, 1996). When relating to risk objects and risk sources, a more systemic approach is proposed and risk is defined as a function of the hazard posed by the risk source and the vulnerability of the risk object (Hauger et al., 2006; Kelman, 2003). It is noteworthy that the two definitions described above are complementary to each other. Each of the definitions has certain advantages in explaining risk characteristics in different applications (Floodsite, 2009).

Figure 3-1 shows the flood risk assessment framework applied in this study. It is an approach for quantifying flood risk in monetary terms based on a combined analysis of flood hazards and vulnerabilities, as suggested by e.g. Haynes et al. (2008), Morita (2008) and Plate (2002). With a given climatic loading (precipitation, in the context of pluvial flooding), the key principle is to assess the hazard and vulnerability characteristics of an area and then link both types of information in a GIS-based risk model.

More specifically, the hazard analysis focuses on characterizing the probability, extent and magnitude of floods. This includes investigating probability distribution of floods, simulating overland flow paths and relevant hazard indicators (e.g. water depth and velocity). Such hazard maps can be simulated by a 1D-2D coupled model, which is available in a number of commercial programs, such as Mike URBAN and MIKE FLOOD (MikebyDHI, 2009) and SOBEK (Deltares, 2010). The 1D sewer model can be used to simulate the underground pipe flow and the 2D inundation model can be used to simulate the water depth and flood extent of the overland flow. The vulnerability analysis focuses on describing the potential adverse effects that can be harmed by the hazard. In most cases, the vulnerability can be presented by the economic, social and ecological costs by means of landuse maps and other information. The adverse effects can be described by the physical damage and intangible losses in the area given exposure by the hazard. The physical damage includes mainly the direct impacts on houses, buildings and public infrastructures. Intangible losses could be the loss of recreational amenities, traffic delay and inconvenience, adverse psychological impacts on people and losses of valuable personal possessions and cultural variables.

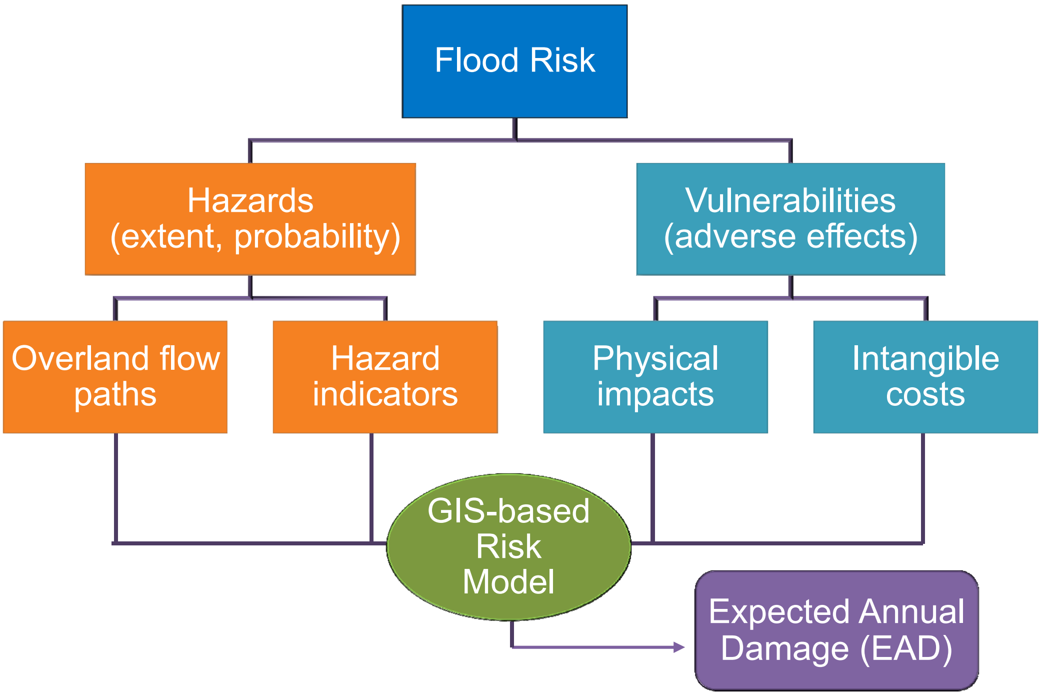

Figure 3-1: Flood risk assessment framework. From Paper I.

The simulated hazard maps and the vulnerability data are further combined in a Geographical Information System (GIS)-based model to assess flood damage as a result of exposure, see an example in Figure 3-2. Appropriate stage-damage functions are used to identify flood damage on vulnerable categories as a function of hazard indicators, e.g. water depths (Dawson et al., 2008; Floodsite, 2009; Freni et al., 2010). This is done by extracting a spatial coordinated layer containing flooded properties of interests on a basis of the stage-damage functions (see Figure 3-2). However, in many cases, such stage-damage functions are unavailable for many urban landuse types. Therefore, a simplified binary approach is often adopted to identify flooded properties by using threshold principle. In other words, for each damage category, uniform unit costs are assigned to the flooded units when the water depth exceeds certain critical thresholds (see Paper I for further details).

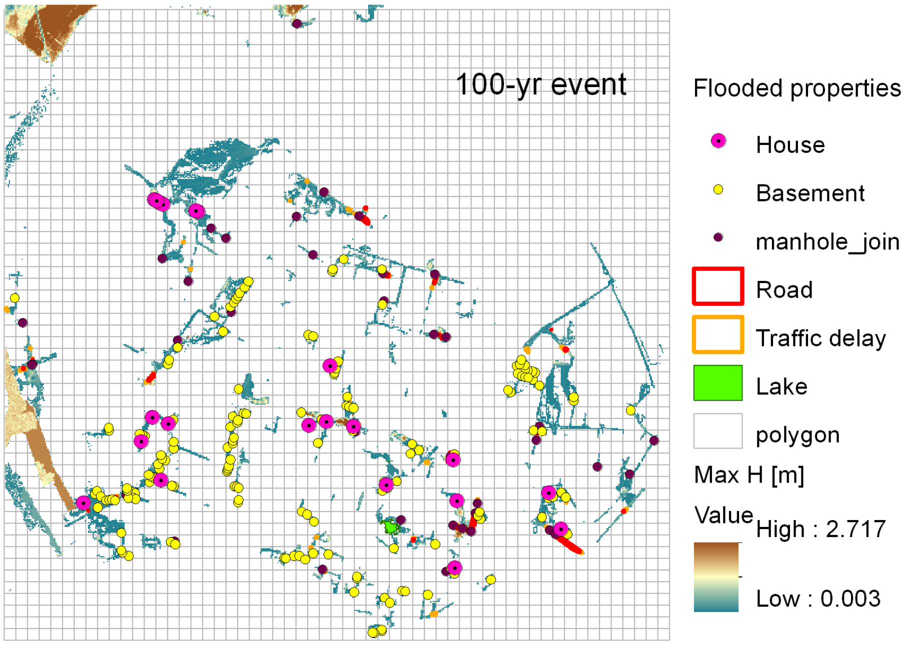

Figure 3-2: Flooded properties identified for a given hazard loading (a 100-yr rainfall event) based on the GIS-based risk model. The background shading area shows the simulated maximum water depth of the given loading using the 1D-2D coupled inundation model. The grid system shows the resolution of the GIS-based model for spatial integration of costs. Adapted from Paper I.

Flood damage costs of a given hazard are calculated by quantifying the flooded properties into monetary terms, and hence, the risk of flooding can be estimated by multiplying the damage costs and the corresponding probability of occurrence per year (see an example in Figure 3-3a) for the given hazard. The same operation can be done for a range of hazard loadings/rainfall events to construct a damage-return period curve (Figure 3-3b) and a risk density curve (Figure 3-3c) to describe the expected flood damage costs and risks as a function of return periods, respectively. The risk density curve gives a description of the contributions of different return periods to the total risk and allows us to identify the events that are of high importance to the flood risk (Merz et al., 2009; Morita, 2008). Furthermore, the risk density curve is expected to change over time due to changes in hazard and/or vulnerability. An increase in hazards will result in a general shift of the risk density curve towards more frequent return periods and also a more peaked curve as a result of amplified exposure due to increased extent and magnitude of flooding. An increase in vulnerabilities such as increased repairing costs will only amplify the existing risk density curve while the occurrence of flood events will remain the same. Appropriate adaptation measures can reduce flood risk by managing hazards and/or vulnerabilities.

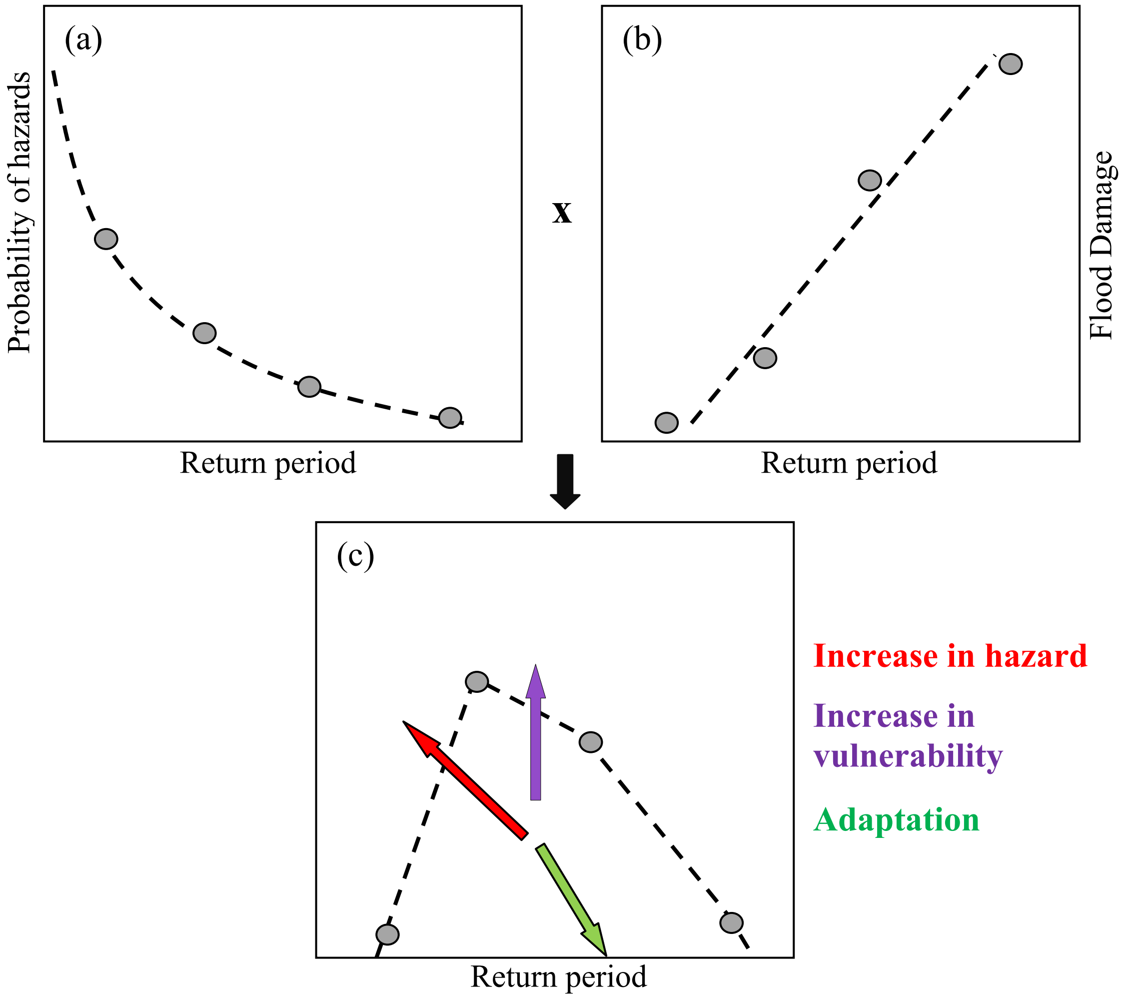

Figure 3-3: Illustration of (a) probability density curve, (b) damage-return period curve, and (c) flood risk density curve as a function of return periods, respectively.

The expected annual damage (EAD), as an important risk indicator, can be estimated by integrating flood damage (D) over occurrence probabilities (p) for an area (A):

$$EAD = \int_A \int_p D(p)\, dpdA$$

However, in reality it is impossible to assess flood damage for a whole range of rainfall events. This means the actual description of flood damage as a function of occurrence probability is not easy to obtain and therefore in most cases only a few points in the relationship are investigated and used to estimate the EAD (Meyer et al., 2009). Moreover, changes in EAD can be used to indicate the performance of adaptation alternatives and to calculate the net benefits of adaptation for subsequent economic analysis (see chapter 3.2).

Besides the integration of flood damage for a large catchment/area, the damage costs can also be integrated into smaller spatial scales to yield a flood risk/EAD map using the GIS-based model, see an example in Figure 3-4. Such a map gives a spatial illustration of the expected annual losses due to pluvial floods and is helpful to identify weak points of the analysed urban drainage system, or provide guidance for allocating priorities of different adaptation actions (de Moel et al., 2009; Plate, 2002). It can be noted from Figure 3-4 that highest EAD does not necessarily locate in places with highest water depth. The flood risk/EAD only occurs in locations where there is an exposure of vulnerability to hazard.

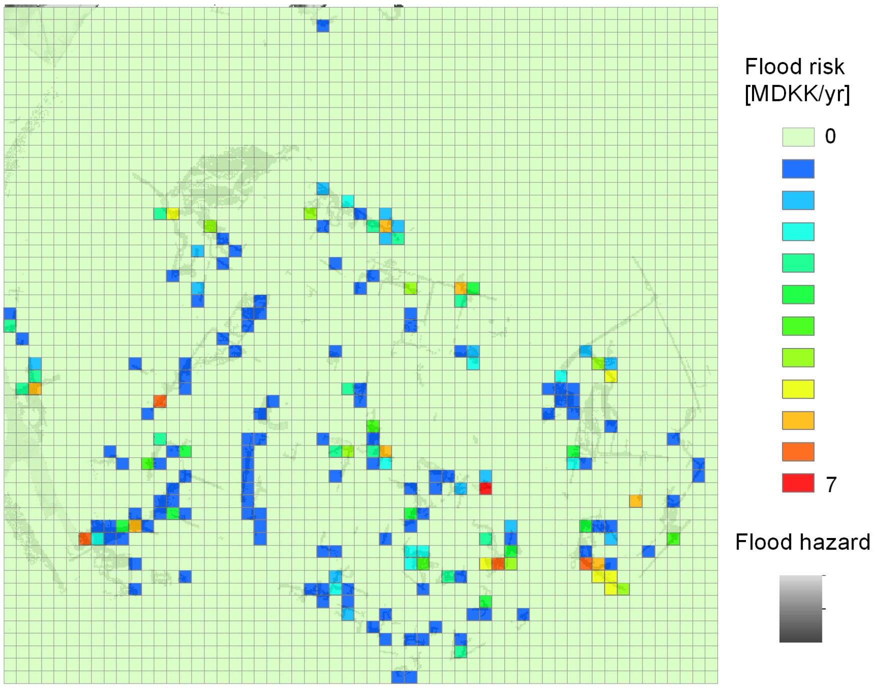

Figure 3-4: An example of EAD map generated from the GIS-based risk model. The map shows a spatial analysis of EAD based on a number of hazard analyses (an example of hazard maps is shown in the shading area).

3.1.2 Verification of flood damage modelling

In the flood risk assessment framework, a prevalent approach is applied by using the state-of-the-art 1D-2D coupled inundation modelling incorporating a staged damage function. Although technologies of the inundation modelling and the damage estimation have taken a leap forward in recent years, calibration and verification of these models are difficult. There is a lack of field data describing the spatial and temporal information of flood characteristics and the corresponding damage consequences (Spekkers et al., 2011).

Data assembled by insurance companies often cover information on several years of claimed damage, which potentially capture the effects of different characteristics of urban flooding at different spatial and temporal scales. As such insurance data may be an important means to characterize urban flooding and to verify the damage modelling approach applied in the risk assessment framework.

Table 3-1 shows a comparison between the identified flooded properties using the GIS-based risk analysis and the geocoded insurance claims obtained from a Danish case study, see Paper III for further details. The insurance data are compared to the model prediction in term of the locations and damage costs of flooded properties. The results are categorized into three hazard groups based on calculated inundation return periods: below 10 years (*Often*), 10-100 years (*Sometimes*) and above 100 years (*Very Unlikely*). The results show that the GIS-based risk assessment has a high potential to identify physical impacts (in particular houses and basements) in terms of flood frequency and location, see an example in Figure 3-5. For the first two hazard groups there is a fairly good statistical agreement between the observed insurance claims and the modelled flood damage. However, it remains a challenge to verify the severity/costs of damage based on the received insurance claims. This indicates a need to include more socioeconomic variables (such as property value and income level) in the damage estimation as well as to improve the collection and analysis of insurance data for model calibration and verification.

Table 3-1: Validation of inundation modelling with geocoded insurance data. The flooded percentage indicates the ratio between the matched and the total expected locations of flooded properties from the risk analysis. For matched locations, claimed insurance costs are assigned to indicate the flood consequence. No costs were assigned to the location, if it did not match with the insurance claims. From Paper III.

Probability		Consequence			Flooded percent.
Frequency	#/year	Expensive >25,000 DKK	Cheap 0-25,000 DKK	No cost 0 DKK	
Often	≥ 0.1	3	11	11	56%
Sometimes	0.1-0.01	12	7	46	29%
Very unlikely	<0.01	8	8	1468	1%

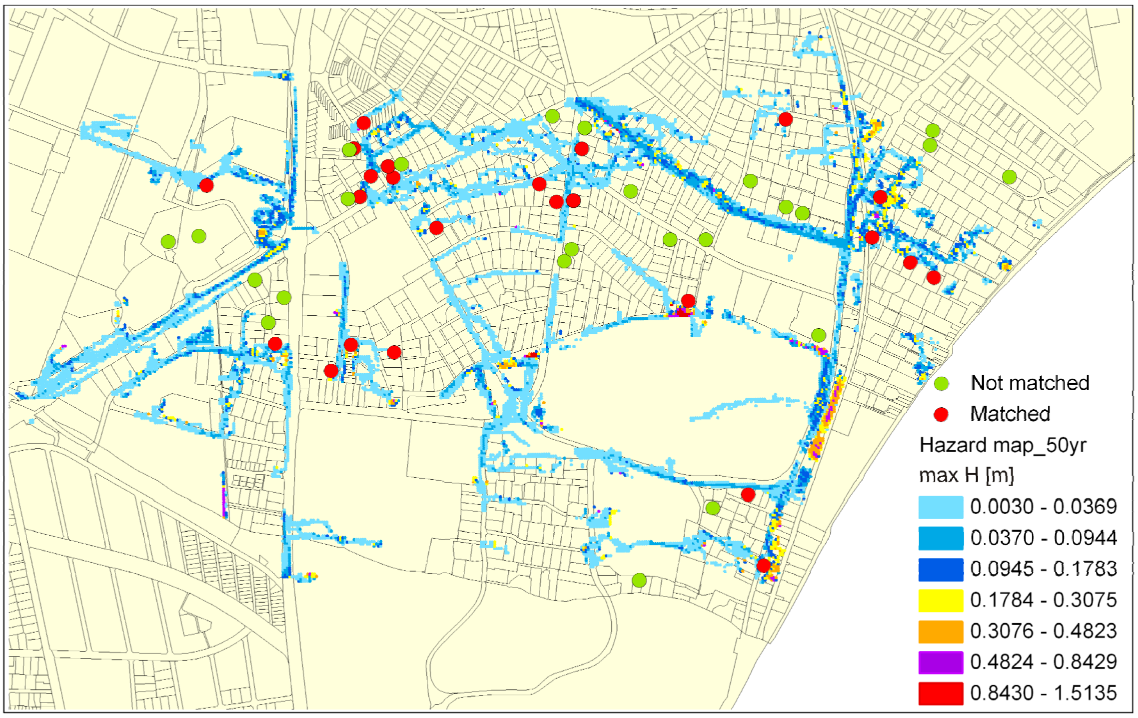

Figure 3-5: Verification of hazard and risk assessment of a 50-yr event by means of insurance data. The red and green dots are the matched and non-matched locations of properties in comparison with the insurance data, respectively. From Paper III.

3.2 Socio-economic analysis of climate change adaptation

3.2.1 Socio-economic framework for adaptation assessment

Socio-economic analysis of adaptation measures can be based on the principles of cost-benefit analysis (CBA). The main rationale of this approach is to evaluate efficiencies of adaptation options by comparing their benefits and costs (Gafni, 2006; Pearce et al., 2006). In the socio-economic framework, benefits are assessed as the difference in flood damage before and after implementing an adaptation option. Costs are investment costs of adaptation. Figure 3-6a shows the socio-economic framework for assessing the benefits and costs, where three scenarios (see Paper I) are involved:

- Baseline scenario (BS) denotes the EAD without planned adaptation in the absence of climate change
- Climate change impacts scenario (CCIS) denotes the EAD as a result of climate change impacts, however, without planned adaptation
- Climate change adaptation scenario (CCAS) denotes the EAD after implementation of a planned adaptation under climate change impacts.

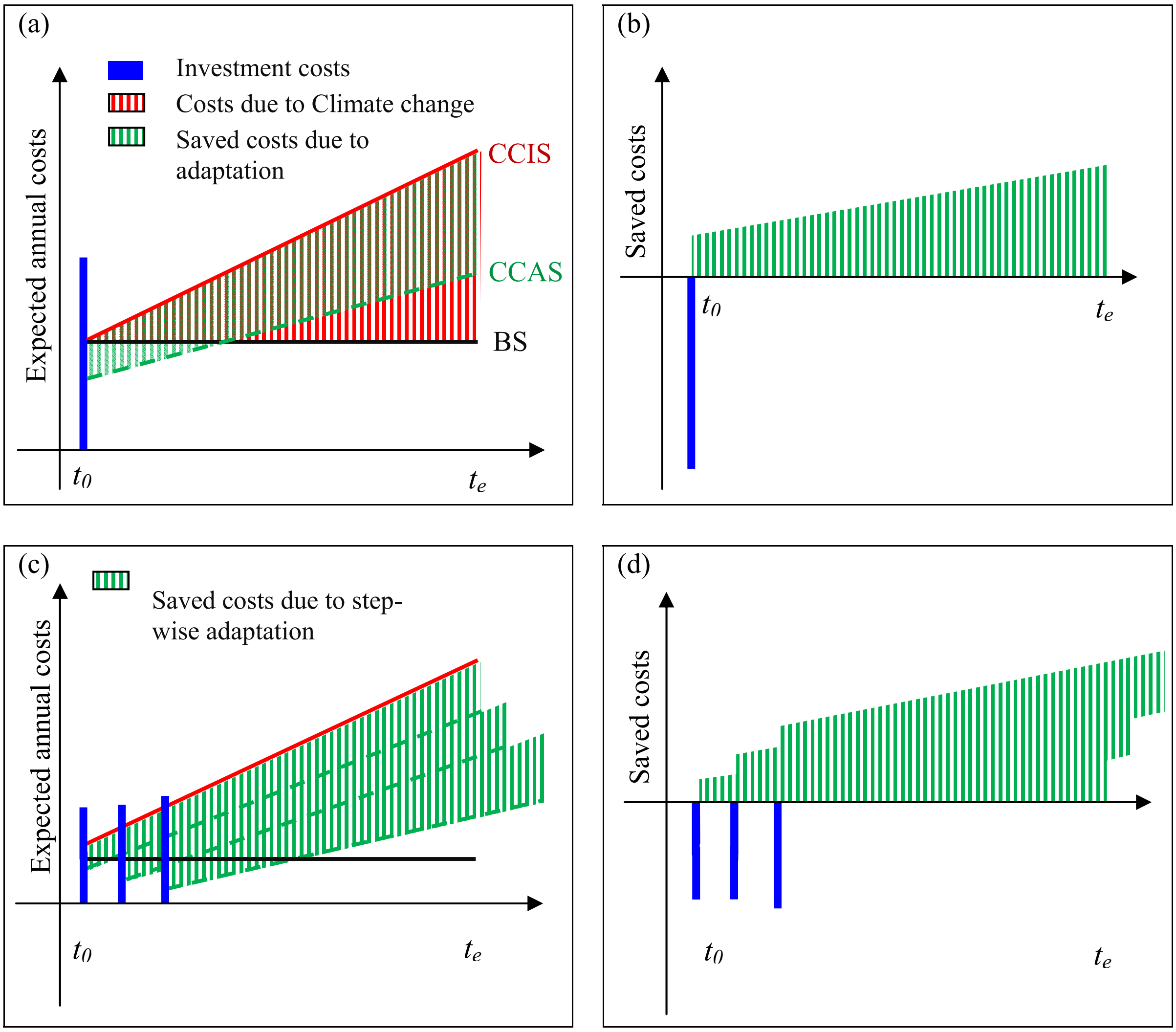

Figure 3-6: Illustrations of the social-economic framework for assessment of (a) one-step lumped adaptation and (c) step-wise adaptation, and investement profiles of (b) one-step lumped adaptation and (d) step-wise adaptation, respectively. Adapted from Paper I and Paper II.

The area between the CCIS and BS curves indicates the additional costs due to climate change impacts. The area between the CCIS and CCAS curves corresponds to benefits of the planned adaptation due to reductions in the EAD. t_0 and t_e denote the start and end year of the planning horizon, respectively.

In the framework it is assumed that climate change impacts/costs evolve linearly over time. This is because that, first of all, a linear function is preferred when there is no clear indication to utilize other functions for climate change impacts (Richard, 1995; Smith et al., 2001). Secondly, as shown in Figure 3-7, assessment of climate change costs is often associated with large uncertainties from e.g. global and regional climate model simulations, hazard assessments, and cost estimation of vulnerable assets. While the description of these uncertainties is important, a linear relationship is a reasonable assumption under such large uncertainties.

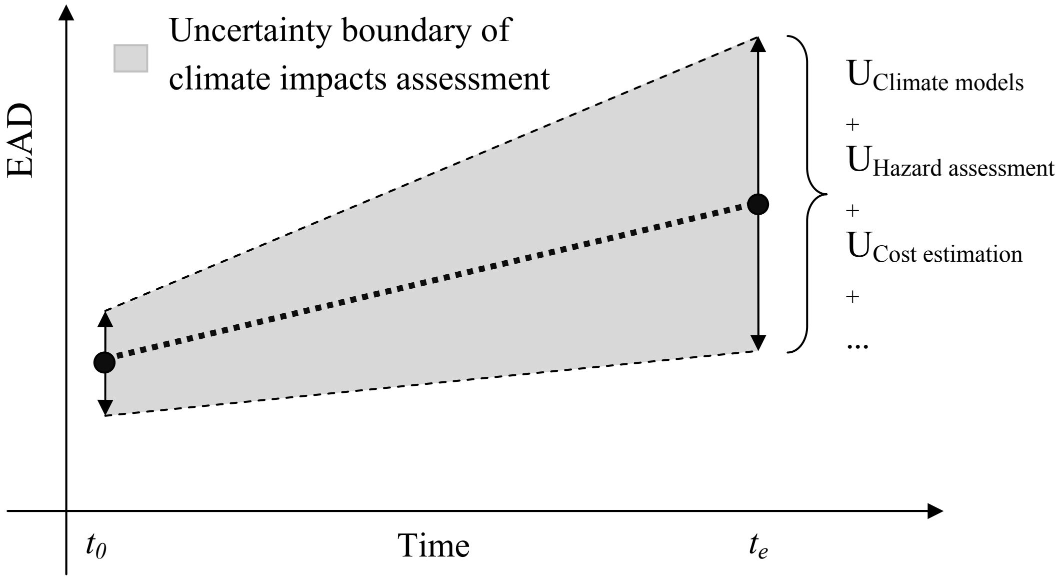

Figure 3-7: Conceptual sketch of temporal development of the uncertainties associated with climate change costs estimation.

Furthermore, to simplify the illustration of the socio-economic framework (Figure 3-6a) it is assumed that no changes apart from adaptation to climate change impacts will occur in the catchment. It is also assumed that the one-step lumped investment will be implemented in the beginning of the planning horizon and therefore benefits are calculated from the point of the investment in time. Based on the three aforementioned assumptions, it is only necessary to calculate the EAD at time t_0 and t_e for the three scenarios. Figure 3-6b summarizes the costs and benefits due to such a one-step adaptation in terms of saved costs.

It is important to note that the framework presented here is not restricted to these assumptions and it is readily extended to cases where these assumptions are not met. For instance, implementation of a non-linear climate change impacts can be incorporated directly by changing the trajectory of the cost curves in Figure 3-6a. Impacts due to gradual city development can be added directly on the original CCAS and CCIS curves by accounting for the changes in hazard and vulnerability in terms of EAD. Changes in adaptation measures, such as a step-wise adaptation, can be incorporated by adding additional points between time t_0 and t_e and recalculating the three scenarios, see an example of the step-wise adaptation in Figure 3-6c. The resulting benefits are therefore piecewise linear with abrupt changes when the adaptation measures are implemented, see Figure 3-6d. The same profile can be applied for other important socio-economic changes during the planning period.

Finally, the benefits and costs are assembled into a net benefits curve on an annual basis, see Figure 3-8. Benefits and costs will accrue over time and discounting is usually applied to express the costs and benefits in their present values in order for comparison (Pearce et al., 2006). Discounted benefits (PV_B) and costs (PV_C) can be estimated by using an appropriate discount rate r over a period t:

$$PV_B = \sum_{t=t_0}^{t_e} \frac{B_t}{(1+r)^t}$$

$$PV_C = \sum_{t=t_0}^{t_e} \frac{C_t}{(1+r)^t}$$

Developments of net benefits of the one-step and the step-wise adaptation are illustrated in Figure 3-8 respectively, showing the impacts on net benefits due to timing of adaptation and the duration of adaptation actions. The main advantages of the step-wise adaptation include better allocations of resources and costs for adaptation measures and providing more flexibility to cope with the uncertainty and irreversibility in the process. Furthermore, it is noteworthy that, in particular for a long-term project, both the shape of the net benefits (NB) curve and the cost-recovery period ($t_{NB=0}$) are highly sensitive to the choice of the discount rate (Almansa and Martinez-Paz, 2011; Pearce et al., 2006). There are many discussions in the literature on how to choose appropriate discount rates for different projects, as outlined in Paper I. In general, for long-term investments (with a lifetime of more than 50 years) in climate change projects, a discount rate of 3% is recommended by the Danish EPA guidelines (Damgaard et al., 2006).

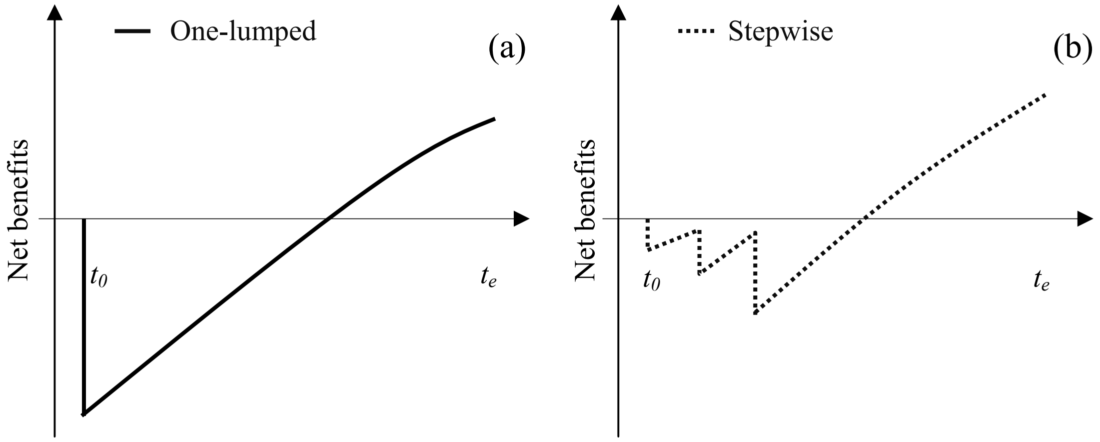

Figure 3-8: Development of net benefits over time of (a) the one-step adaptation and (b) the step-wise adaptation.

3.2.2 Economic efficiency indicators in the CBA context

In the cost-benefit analysis, there are a number of decision rules that can be used for comparing benefits and costs from a welfare economic point of view (Pearce et al., 2006). Two most commonly used indicators are Net Present Value (NPV) and Benefit-cost ratio (B/C). Table 3-1 illustrates a comparison between the NPV and the B/C rules. Note that the table only gives very crude information and guideline on the efficiency indicators, the actual choice of appropriate decision rules for CBA can be very complex and context dependent (Messner et al., 2006; Pearce et al., 2006; Tung et al., 1993).

The NPV indicates the net benefits of a project and is calculated by subtracting the gross costs from the gross benefits in their present values. A project with positive NPV implies that the project is economically attractive to implement. The benefit-cost (B/C) ratio is calculated by dividing the discounted benefits by the discounted costs. It is a comparative index describing the output-input ratio of a project. A project can be recommended for implementation if its B/C ratio is greater than 1 and rejected otherwise.

The NPV will always be used in the cost-benefit analysis to normalize economic flows that occur at different points in time and give a description of the total profit of a project (Pearce et al., 2006). In particular, when there are adequate resources for implementation, NPV should be used as the decision rule for ranking projects in order to maximize the net benefits. When budget constraints exist, the B/C ratio is more applicable to prioritize projects with higher unit returns. However, when choosing between mutually exclusive projects, the B/C rule can mislead the decision making and in such a case the appropriate decision rule is to choose the project with the largest NPV (Bacon, 1977; Gould, 1972; Pearce et al., 2006).

Table 3-2: A comparison between the NPV and the B/C rules in the cost-benefit analysis. PV_B and PV_C denote the discounted benefits and costs, respectively.

Indicator	**NPV**	**B/C**
Formula	$NPV=PV_B-PV_C$	$B/C=PV_B/PV_C$
Economic indication	Net benefits	Unit efficiency
Decision criterion	NPV>0	B/C >1
Applicable circumstances	Adequate resources; mutually exclusive projects	Budget constraints

In addition, the two decision rules can be used, not only for evaluating economic performance of a single project, but also for ranking/prioritizing measures when there are multiple projects or multiple steps in a project. The practical application can be very complex; nevertheless, the basic rule is to adopt all projects with positive B/C ratio and then give higher priority to measures with higher NPV to ensure the correct combination of projects (Pearce et al., 2006; Turner et al., 1993).

The decision criteria discussed in the chapter are aimed to help decision makers to prioritize projects based on cost-benefit grounds. It is essential to be aware that the actual decision making depends also on many other influencing factors that are difficult to take into account in the CBA. In such a context, other decision making support techniques, e.g. multi-criteria analysis (MCA), can be considered to incorporate multiple types of objectives or disciplines in the decision making process.

3.3 Case studies

A Danish case study (Skibhus) has been applied to test the feasibility of the introduced framework and assess the performance of alternative adaptation measures.

The catchment of Skibhus is located in the northern center of Odense, Denmark, see Figure 3-9. It is an urban area consisting of mainly single residential houses. Industrial or other commercial activities are marginal in the area. The catchment is about 389 ha with a population of 11809 people. The area is well developed and municipal plans foresee no changes in the city layout and socio-economic conditions in the foreseeable future. The sewer network is a combined system that conveys water from east to west towards the outlets near the Odense Harbour. The elevation of the catchment varies from 0 to 20 m above mean sea level. The planning horizon of climate adaptation is from year 2010 to 2100.

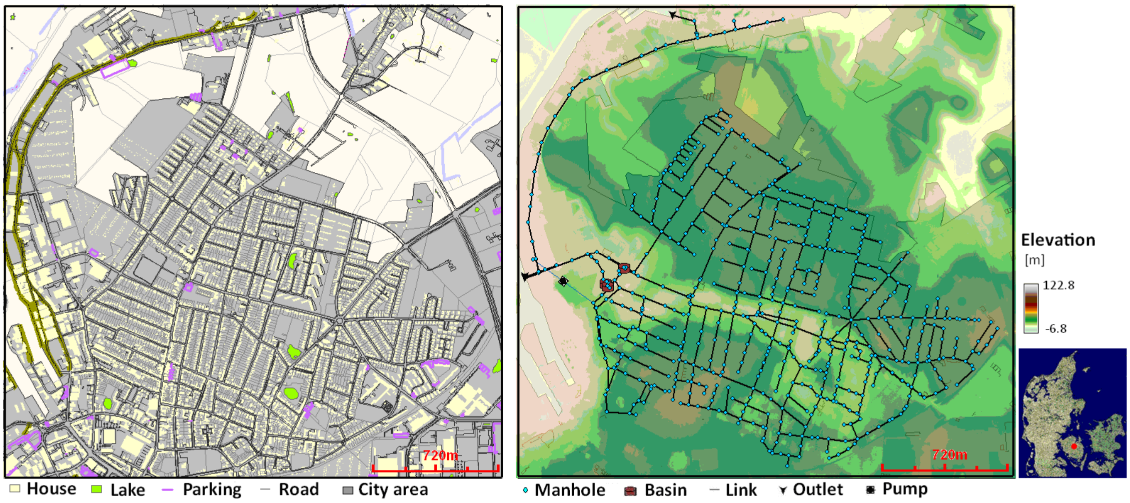

Figure 3-9: An overview of the urban layout map (a) and digital elevation map with sewer network (b) of the catchment of Skibhus. From Paper I.

Hazard and vulnerability analyses indicate that the drainage capacity in the catchment is in general too small to cope with increasing rainfalls and climate change impacts will lead to a significant increase in EAD due to increased occurrences of flooding, see Paper I. Figure 3-10 illustrates the calculated damage-return period curves and risk density curves for the present and future climate assuming no climate change adaptation. It can be seen that due to climate change, a design intensity currently corresponding to a 100-yr event will correspond to a 20-yr event in a 100-yr horizon; similarly, a design intensity currently corresponding to a 10-yr event will correspond to a 3.5-yr event after 100 years. Using the flood risk framework, the EAD under current climate is calculated to be 3.9 MDKK (10^6 Danish Kroner) while the EAD in year 2100 has increased to 9.3 MDKK due to climate change impacts.

Two adaptation options, namely pipe enlargement and infiltration, are applied in the case study. Pipe enlargement is modelled by increasing the pipe diameter of the sewer network in the 1D model. Infiltration is aimed at reducing the hydrological load of the existing drainage system and is modelled by reducing the degree of impervious area of selected subcatchments in the catchment. Furthermore, each measure is applied based on two decision criteria: D1) overall adaptation and D2) economically optimal adaptation. D1 is formulated based on principles of equity and corresponds to a fixed minimum service level corresponding to no damages at a 5-yr event in present climate, while D2 only considers adapting at locations where adaptation is economically most profitable from an overall perspective. More elaborations on the applied adaptation measures and the two decision criteria can be found in Paper I and Paper II.

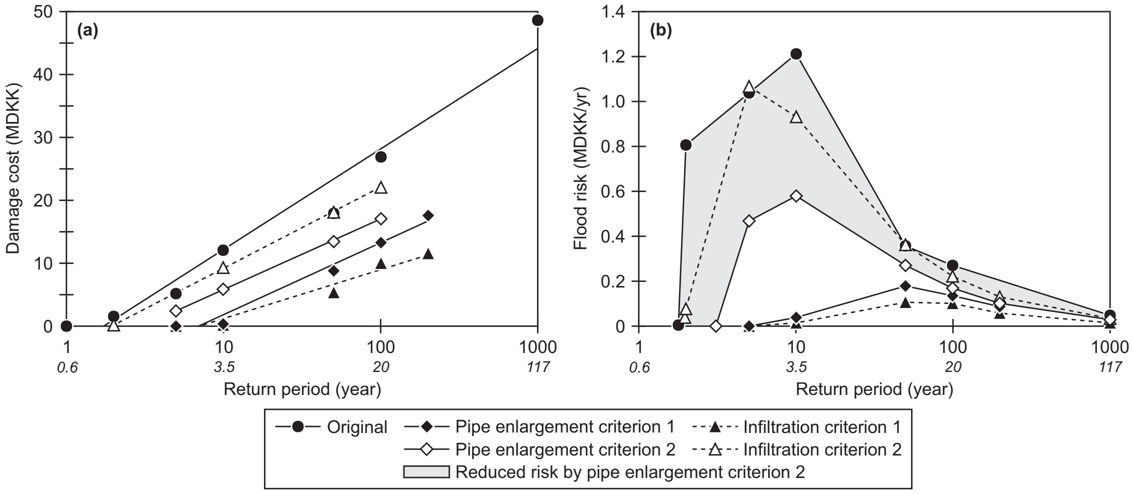

Figure 3-10: Assessed damage-return period curves (left) and annual risk density curves (right) for the baseline scenario and two adaptation options under D1 and D2 without and with climate change impacts. The return period indication on the horizontal axis in black colour shows the extreme external loading under current climate conditions and the red one indicates the anticipated climate in 2100. The area between the original risk curve and the reduced risk curve indicates the benefits of investment in terms of reduced EAD. From Paper I.

Socio-economic analyses of the benefits and costs of the two proposed adaptation options are shown in Figure 3-11. It can be seen that the required investment costs are much higher in D1 in comparison with D2. However, there is less damage saved based on D2, indicating that more losses are allowed to occur based on the economically optimal approach. The estimation of net benefits (with a discount rate of 3%) of the two options is shown in Figure 3-11 for D1 and D2, respectively. The results show that in general it is recommended to adapt in the catchment as both calculated net benefits are positive at the end year. It can be noted that higher net benefits are achieved based on D2, which implies that smaller upgrading of the system is more economically beneficial. In addition, the results show that pipe enlargement is more cost-beneficial in comparison with infiltration to handle climate change in the catchment.

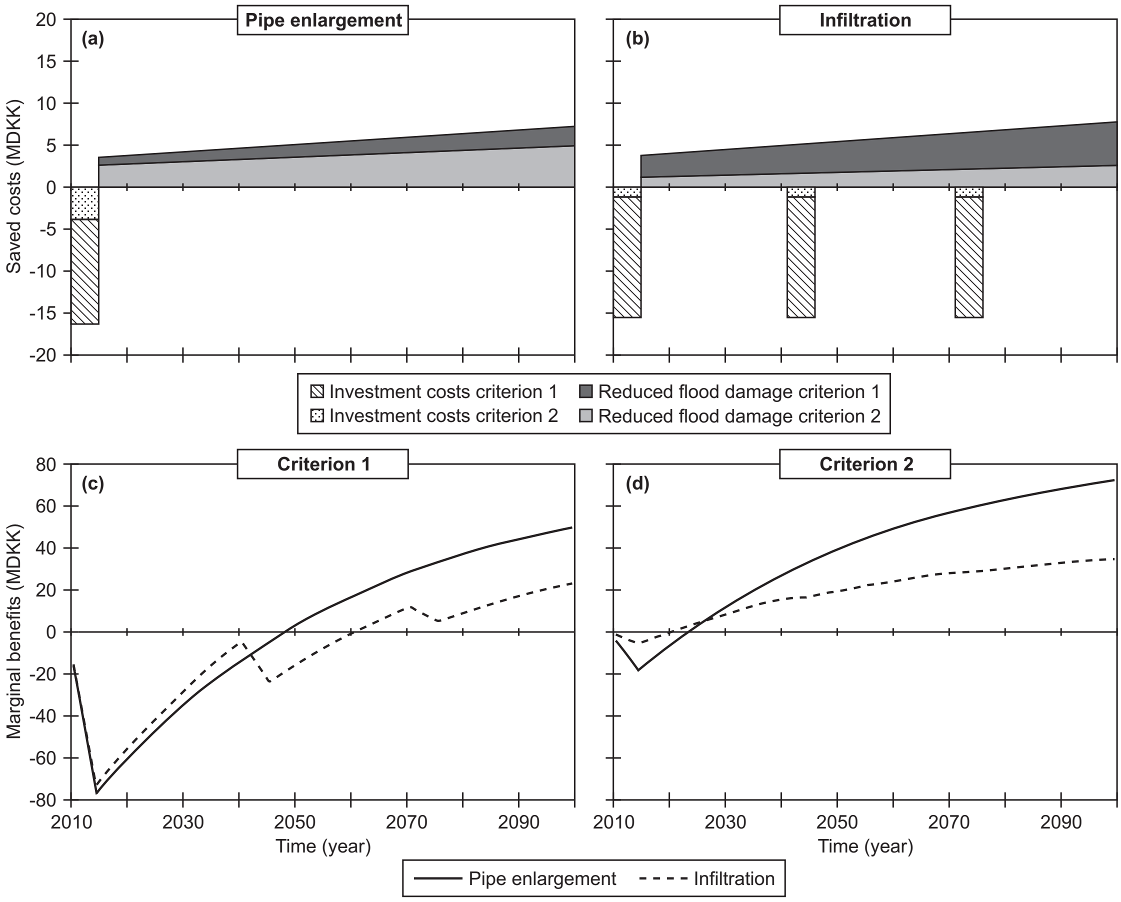

Figure 3-11: Illustration of investment costs and adaptation benefits due to (a) pipe enlargement and (b) infiltration under climate change (CC) impacts. The net benefits curves of the two options are calculated for (c) D1 and (d) D2, respectively. Adapted from Paper II.

The case study shows that the introduced framework provides guidance on adaptation strategies. The risk-based cost benefit analysis shows the capability of evaluating the economic efficiency of different adaptation approaches by giving more insights into their pros and cons. The introduced framework provides a useful tool that can support decision making in the urban drainage adaptation design under climate change impacts.

4. Uncertainty assessment of climate change adaptation options

As shown in the previous chapter, assessment of adaptation options often demands a comprehensive risk-based economic analysis to indicate the efficiency of alternative options (Apel et al., 2004; Beven, 2009). Such an analysis is often complicated by the large uncertainties associated with the assessment of the response impacts of present and future hazard and vulnerability conditions (Freni et al., 2010; IPCC, 2007; McMillan et al., 2011; van der Keur et al., 2008). As a result, the final estimate is in fact a very uncertain outcome representing a propagation of all inherent uncertainties in the analysis (de Moel and Aerts, 2011).

It is a very challenging issue to identify robust adaptation options in light of the many and substantial sources of uncertainty. This requires a better understanding of not only the characteristics and dimensions of associated uncertainties, but also the roles and impacts of these uncertainties in the analysis. According to Walker et al. (2003) and Refsgaard et al.(2012), uncertainty can be described in three dimensions: location, level and nature. The three-dimension concept allows for a better characterization and communication of uncertainties in the analysis. More importantly, different uncertainties can influence decision making in different manners. It is vital to study their effects on the assessment in order to prioritize critical uncertainties. Such important uncertainties need to be communicated explicitly to decision makers, so that additional efforts can be engaged to improve the quality of decisions in relation to climate change.

When planning climate adaptation strategies there are often a number of scenarios constructed in order to identify a ‘best’ solution based on a comparative assessment. In such a context, two types of uncertainties are essential to distinguish: the overall uncertainty of an individual scenario and the marginal uncertainty when comparing adaptation scenarios. The first type of uncertainty provides an overall description of the economic consequences of the investigated scenario, which has an influence on the choice between action and in-action. The marginal uncertainty between compared scenarios is of more interest to decision makers when prioritizing adaptation strategies once the decision of action is taken (Hauger et al., 2002; Vezzaro et al., 2012).

In this chapter, first of all, the three dimensions of uncertainty in relation to climate adaptation decision making are described. Next, an integrated uncertainty analysis is introduced to assess the overall and marginal uncertainties of climate adaptation assessment. A sensitivity analysis is incorporated in the procedure to assess the relative importance of inherent uncertainties in the analysis. At last, some results achieved by applying the aforementioned methodology in a Danish case study are described.

4.1 Dimensions of uncertainties in relation to climate change adaptation assessment

Figure 4-1 shows the applied three-dimensional concept for characterizing uncertainty according to its location, level and nature (Refsgaard et al., 2012; Walker et al., 2003).

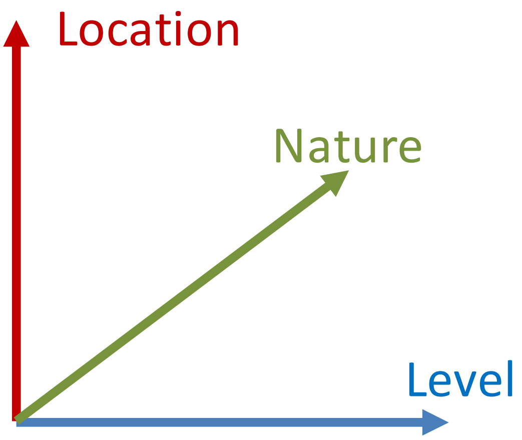

Figure **4-1**: The three dimentions of uncertainty (Walker et al., 2003).

The ***location*** of uncertainty implies where the uncertainty manifests itself in the model. The actual locations of uncertainty may vary from case to case; however, the most common locations with respect to climate change adaptation assessment consist of context, model structure, inputs, parameter, and model outcome:

- The context implies the framing or boundaries of the adaptation assessment. In other words, the context is typically relevant to the scope of the analysis. This includes, for example, what types of damage costs should be taken into account in the assessment? What kinds of economic criteria should be adopted for selecting adaptation strategies?

- The model structure uncertainty may arise when there is an incomplete understanding of the internal relationships and structures of the adaptation assessment. Such uncertainties may also occur due to a simplification of model process.
- Input uncertainties commonly exist in the climate adaptation assessment. For example, there are always large uncertainties associated with input socio-economic data for damage estimation. The landuse maps and digital elevation models for vulnerability analysis are often uncertain.
- Parameter uncertainty may arise when there are imperfect descriptions of model parameters. For example, there is often an uncertainty associated with descriptions of hydraulic and hydrological parameters in flood hazard assessment, e.g. imperviousness, manning number.
- The model outcome uncertainty is the uncertainty propagated through the whole assessment process. It accumulates uncertainties from all of the aforementioned locations. The overall uncertainty mentioned previously is one type of the outcome uncertainties.

The ***level*** of uncertainty can be described by a progression from determinism to total ignorance, see Figure 4-2. Determinism describes an ideal and unattainable situation where everything is known precisely, and total ignorance implies a state of complete lack of awareness of imperfect knowledge (van der Keur et al., 2008). In the progression, statistical uncertainty denotes any uncertainty that can be described in statistical terms. Scenario uncertainty implies a state that possible outcomes are known; however, the probabilities of these outcomes are not well understood. Recognized ignorance denotes a state that there is an awareness of imperfect knowledge, but not being able to categorize it further. In the climate adaptation assessment, many uncertainties are described in the form of statistical and scenario uncertainties. There are also uncertainties described qualitatively to indicate the possibility of various outcomes (Brown, 2004). Recognized uncertainties also exist, however, it is generally difficult to characterize such uncertainties in the assessment.

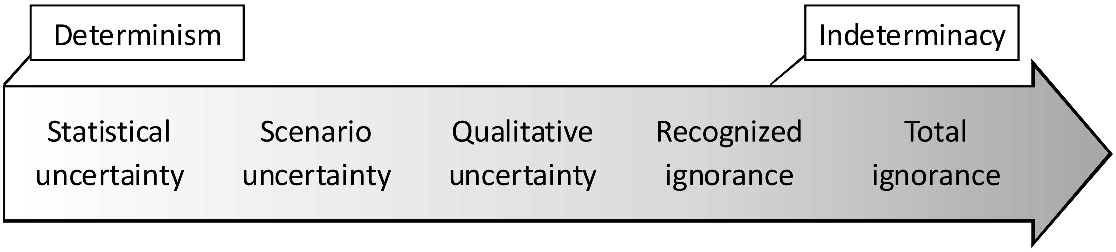

Figure 4-2: Levels of uncertainty (Refsgaard et al., 2012).

The ***nature*** of uncertainty distinguishes uncertainty between epistemic uncertainty due to imperfect knowledge of the system and variability uncertainty as a result of inherent variability of the system. The epistemic uncertainties are reducible, while the others are not. Nevertheless, it is always costly and time consuming to take further data collection and treatment to reduce uncertainties (Hancock, 1998). Therefore, before taking any actions, it is essential to find out if further studies on uncertainty can improve the decisions on climate adaptation and what are the corresponding costs (Loucks et al., 2005).

4.2 Framework for uncertainty assessment

The three-dimensional conceptual framework provides an important tool for comprehending, communicating and discussing the uncertainties associated with climate change adaptation. However, in many cases, such a framework fails to give further guidance on how to choose feasible/robust solutions for climate adaptation in the context of uncertainty. It is therefore of special interest to develop an approach to assess and quantify the effects of the uncertainties to characterize their roles in the evaluation process.

It is widely acknowledged that incorporating Monte Carlo techniques in risk-based economic analysis provides a systemic assessment of combined effects of multiple sources of uncertainties in the evaluation procedure (Almansa and Martinez-Paz, 2011; Balcombe and Smith, 1999; Belli, 1996). The risk-based economic framework (Chapter 3) is therefore extended by embedding it in a Monte Carlo simulation to estimate the overall uncertainty propagated through the evaluation. A sensitivity analysis is also incorporated in the framework to assess the relative contribution of input variables in the assessment.

When planning climate change adaptation strategies it is often necessary to compare a wide range of options to identify an optimal solution, by using appropriate evaluation criteria. Decision makers tend to favour actions with high economic benefits and short payback time. In this study, three economic indicators are chosen to provide such information for use in decisions. They are NPV_i and $T_{NPVi=0}$ describing the assessed net benefits and cost-recovery period of the i'th individual adaptation option, respectively, and ΔNPV_{ij} denoting the difference in calculated net benefits when comparing adaptation alternatives. It is noteworthy that NPV_i and $T_{NPVi=0}$ provide information to decisions on action or in-action, while ΔNPV_{ij} distinguishes different alternatives for adaptation and hence a measure of the relative cost efficiency of the scenarios.

Figure 4-3 describes how uncertainty bounds of the three indicators are assessed based on a stepwise uncertainty analysis. The analysis investigates a complete procedure of various elements in the adaptation process, representing climatic, hydrologic and hydraulics process, hazard modelling, vulnerability assessment as well as socio-economic estimation of costs and benefits. Uncertainties of each component are explained according to the aforementioned three dimensions, more details can be found in Paper IV.

4.2.1 Uncertainty associated with hazard assessment

Climatic loadings

Rainfall, being the climatic loading for pluvial flooding, is estimated based on a comprehensive statistical analysis of historical rainfall measurements. Such an estimation often involves substantial uncertainties from e.g. observation measurements, data selection and treatment, statistical modelling of limited observed climatic events (La Barbera et al., 2002; Mikkelsen et al., 1996). When assessing climate change impacts on future precipitation extremes, there are considerable uncertainties associated with the assessment, including uncertainty from e.g. the choice of temporal and spatial resolutions, the input parameters and scenarios, downscaling and extrapolation methods for urban hydrology applications (Gregersen and Arnbjerg-Nielsen, 2012; Knutti et al., 2010; Willems et al., 2012a).

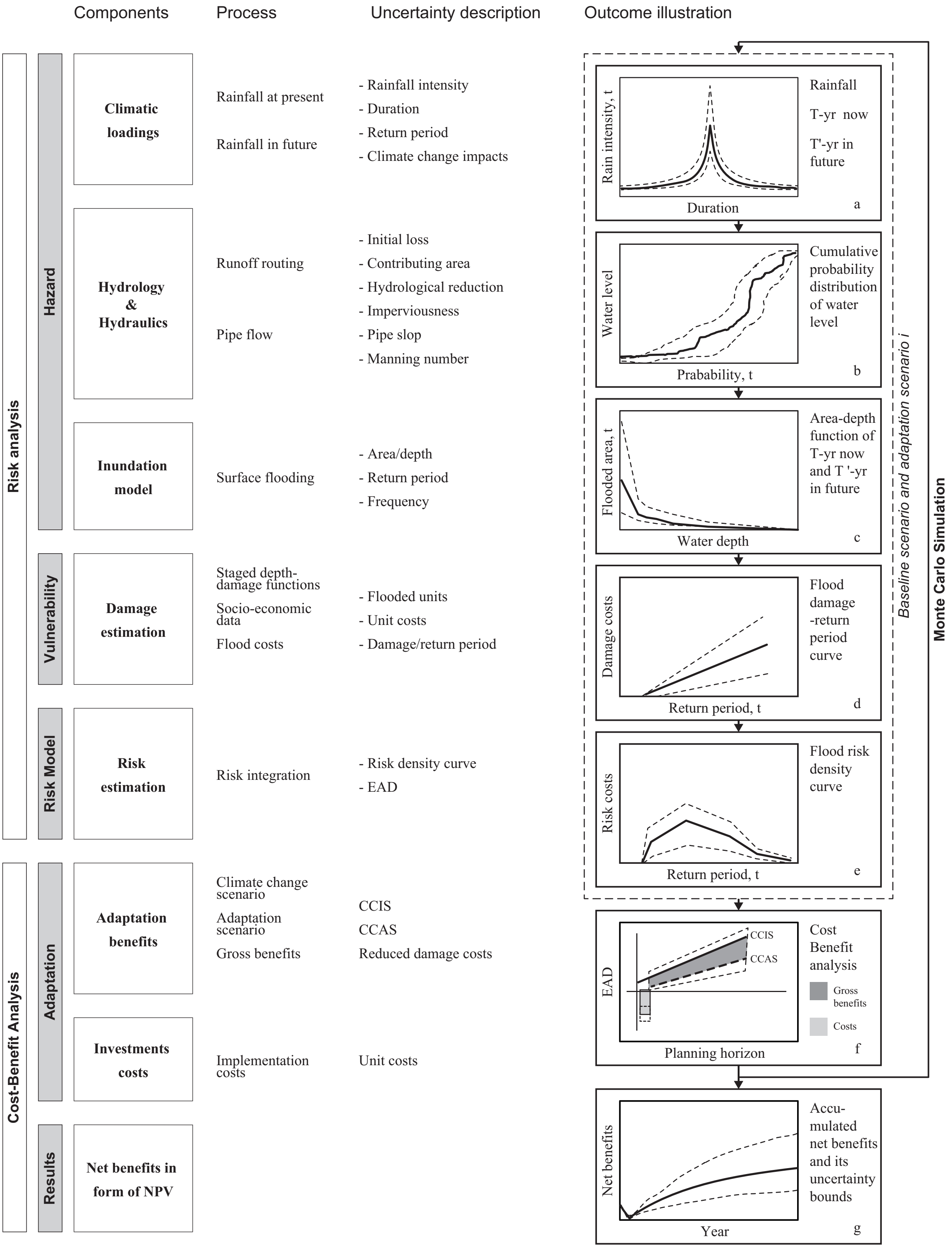

Figure 4-3: Uncertainty analysis of climate change adaptation assessment by Monte Carlo simulations. From Paper IV.

The level of uncertainty associated with present and future rainfall estimation varies from statistical uncertainty to total ignorance. For example, the observation measurements contain mainly statistical uncertainty while the downscaling methods include both scenario uncertainty and recognized ignorance. Some of these uncertainties can be reduced by improved knowledge, such as the choice of spatial resolution.

Figure 4-3a shows the uncertainty inputs of present rainfall in terms of design intensities. The uncertainty associated with climate change impacts is shown by the changes in return periods in this study.

Hydrological and hydraulic processes

Uncertainty presents in all stages in the hydrological and hydraulic processes. It is difficult to achieve a good description of runoff routing and flow dynamics in the system due to uncertainties associated with input parameters, model structure setup, process descriptions and initial conditions setup (Arnbjerg-Nielsen and Harremoes, 1996; Beven and Freer, 2001; Lei, 1996; Wood, 1976). The level of uncertainty varies from case to case and sometimes needs to be characterized qualitatively. Most of the uncertainties can be reduced by engaging more research and empirical efforts.

As a result of combined effects due to uncertainty of rainfall and hydrological and hydraulic process, the water level in manholes can be described with a cumulative probability distribution, see an example in Figure 4-3b.

Inundation modelling

Simplified approaches are often applied for flood inundation modelling due to limited knowledge on system setup as well as heavy computing demand of advanced methods (Freni et al., 2010; Koivumaki et al., 2010; Mark et al., 2004). Uncertainties of key variables, e.g. digital terrain model (DTM), may introduce significant variability in the risk mapping in terms of depth and extent of flooding (Koivumaki et al., 2010; Petrow et al., 2006). The level of uncertainty is mainly statistical uncertainty.

The final outcome of the hazard analysis is a staged area-depth relationship, showing the flooded area as a function of flow depth for a given return period (see an example in Figure 4-3c). Uncertainty bounds of such a relationship represent uncertainty propagation throughout the whole hazard assessment.

4.2.2 Uncertainty associated with vulnerability assessment

Stage-damage functions

Several types of stage-damage functions exist to assess flood damage as a function of risk indicators, such as depth, velocity, and duration (Freni et al., 2010; Meyer et al., 2009). Both epistemic and variability uncertainties associated with the estimation of these stage-damage functions due to limited observations, applied mathematical approaches, poor knowledge of variation of studied damage as well as the unpredictable nature of human and societal behavior in response to flooding (Floodsite, 2009; Freni et al., 2010; Merz and Thieken, 2009). The level of uncertainty ranges from statistical uncertainty to recognized ignorance.

Flood damage-return period function

A flood damage-return period curve can be constructed to describe flood damage as a function of return periods. In general, return periods and the resulting damage are positively correlated indicating larger precipitation events generally lead to higher flood damage costs. Besides the uncertainties related to damage identification and damage estimation, there is always an uncertainty associated with the statistical description of the damage-return period function. Furthermore, city development in terms of socio-economic development, population growth and urbanization is anticipated to have impacts on the damage-return period function. For example, changes in city layout will directly affect the exposure of vulnerable assets to hazards. Economic growth will impact the costing of damage. The highest level of the uncertainty is evaluated to be recognized ignorance and the nature of uncertainty can be characterized as both epistemic and variability uncertainty.

Uncertainty description of the damage-return period function involves both statistical and scenario uncertainties, see an example in Figure 4-3d. It is necessary to note that the uncertainty bounds of the damage-return period function represent a joint impact from hazard and vulnerability analyses.

4.2.3 Uncertainty associated with risk assessment

Besides the uncertainty associated with the costing of damage the probability function of climatic loadings will vary in the future due to climate change impacts. As a product of combined hazard and vulnerability assessment, the uncertainty quantified for risk density functions (Figure 4-3e) combines uncertainty related to not only the damage-return period functions, but also the climate change impacts. Furthermore, the combined uncertainty will also be transformed into the EAD estimates used in the subsequent economic analysis of climate adaptation benefits, see Paper IV for further details.

4.2.4 Uncertainty in relation to cost-benefit analysis

There are a large number of location uncertainties in the CBA. For instance, the assessment of costs and benefits to a great extent depends on the scope and framing of applied framework. Adaptation benefits can be calculated as avoided flood damage within the hydrological context while benefits can also be assessed in a broader context by taking into account e.g. recreational values and environmental assets. The investment costs of adaptation are also strongly context dependent. What's more, different interpretations of economic reality may lead to a highly uncertain decision making process. For instance, decision makers are likely to adopt a different adaptation option when different decision rules are used. Therefore, there may be a large variation in estimated benefits and costs, see an example in Figure 4-3f. The highest level of uncertainty can reach recognized ignorance.

As the outcome of the assessment framework, the three economic indicators are dependent values accounting for uncertainties propagated through the whole procedure. With Monte Carlo techniques, a probability description of uncertainty of these estimates can be obtained, see an example of calculated uncertainty bounds of NPV_i over time in Figure 4-3g. Compared to the single-value estimates, this gives supplementary information to decision making process where the uncertainty impacts are highlighted.

Furthermore, when there is more than one adaptation option to be analysed, all options must be run simultaneously to allow for a direct comparison of their efficiency for each simulation. In doing so, it is also possible to level out the uncertainties that are only significant for the overall uncertainty of individual adaptation scenario and therefore identify critical uncertainties that matter for the decision making.

4.2.5 Sensitivity analysis

To enable an identification of key sources of uncertainty in the framework, a simple sensitivity approach documented by Merz and Thieken (2009) is applied. The relative role of individual input variable is estimated based on its impacts on the final estimates, such as NPV_i as an example. The basic procedure of the sensitivity analysis is described in the following:

1) Calculate the maximum uncertainty range of the final estimate (MUR_{NPV_i}) when uncertainties of all input variables are taken into account.
2) To assess the relative role of a certain input variable, it is necessary to calculate the reduced uncertainty range of the final estimate (RUR_{NPV_i}) by using the best estimate of variable of interest, while retaining all other uncertainties in the simulation. The relative role of the variable of interest can then be calculated as: $(MUR_{NPV_i} - RUR_{NPV_i})/MUR_{NPV_i}$.
3) Repeat step 2 for other input variables.

4.3 Case study

4.3.1 Study area and adaptation options

An uncertainty analysis is applied to the assessment of climate adaptation in the catchment of Skibhus, Odense. Previous economic calculation indicates that pipe enlargement is more cost-beneficial in comparison with local infiltration to comply with a 5-yr minimum service level in the area (Chapter 3.3). However, no further information was provided regarding the uncertainty of the estimates and the robustness in relation to decision making. This study is therefore aimed to quantify the uncertainty bounds of the economic estimates.

4.3.2 Assumptions and input data

Several assumptions are applied in the case study due to e.g. limited information on input variables, inadequate knowledge of system setup, and computational demanding of advanced modelling. Some of the assumptions are used to simplify part of the economic assessment. For example, a log-linear relationship is applied for the damage-return period description. Climate factors are used to describe a bijective change in return periods due to climate change impacts. In the vulnerability assessment, a simplified relationship for damage estimation is applied due to a lack of knowledge of a reliable regional stage-damage function in the case study. In the particular context, a 'threshold water level' is used to identify flooded units for a certain vulnerable category. Unit repairing costs are then used to assess the costing of damage based on identified flooded units. More details on applied assumptions and simplifications see Paper IV.

Uncertainty descriptions of six key input variables are needed for Monte Carlo simulation, which are design rainfalls, climate factors, threshold water levels, unit repairing costs, discount rate, and investment costs of the two adaptation options. In the Monte Carlo simulation it is required to specify probability distributions of all inputs (Refsgaard et al., 2007); therefore, all uncertainties in the three dimensions must be modelled and converted into the statistical level in order to apply the Monte Carlo approach. In this study uncertainties of the six input variables are described statistically by means of either triangular or risk cumulative distribution functions, see Paper IV. Furthermore, high correlations are assigned to each input category in the Monte Carlo simulation.

4.3.3 Results of uncertainty assessment

The calculated flood damage-return period functions for the BAU and the two adaptation options are shown in Figure 4-4, left. The results show that there are large uncertainties associated with the damage-return period functions. However, both adaptation measures help to reduce flood damage costs to a great extent. Annual risk density curves were calculated subsequently to show flood risk as a function of return periods, see Figure 4-4, right. It can be seen that a large risk reduction can be achieved by both measures. The assessed future risk levels in year 2100 (the light grey shadings) under both adaptations are even lower compared to the current risk level under the BAU scenario (see the green shading). This indicates that although there are still uncertainties associated with future flood risk, the proposed adaptation measures are fairly helpful and sufficient to maintain the risk at an acceptable level. Therefore future risks can be managed by the proposed adaptation even in situations of uncertainty.

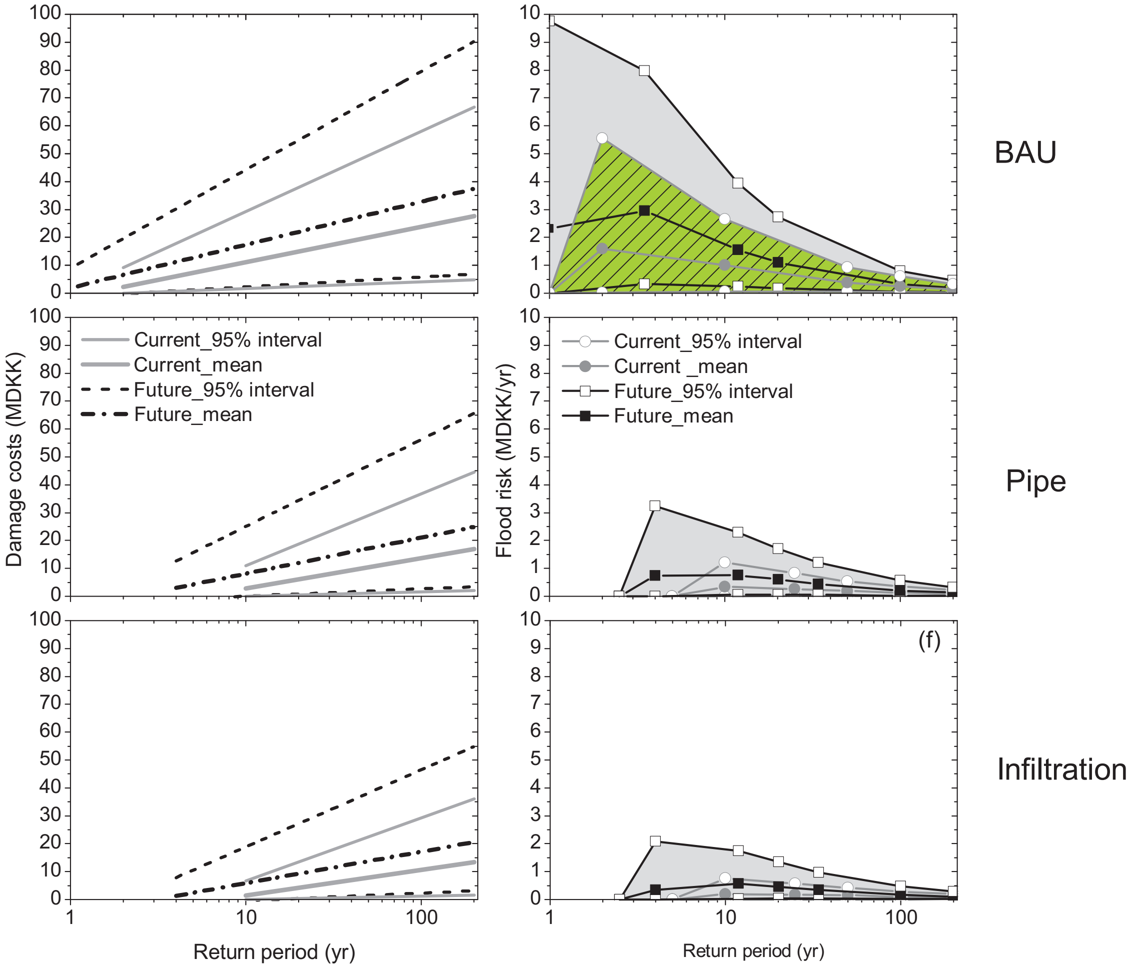

Figure 4-4: Assessed uncertainty bounds of damage-return period functions (left) and annual risk density curves (right) of the BAU and the two adaptation scenarios assuming current and future climatic conditions, respectively. From Paper IV.

Figure 4-5 shows the calculated uncertainty bounds of the individual net benefits, ΔNPV and cost-recovery year of the two adaptation options. In all cases, there is a significant difference between the low- and high- extreme values of the overall uncertainty of individual scenario, which matters for a choice between action and in-action. It should be noted that although local infiltration has larger impacts on risk reduction (see Figure 4-4, right); its net benefits become much lower in comparison with pipe enlargement when taking into account the required investment costs.

The ΔNPV between the two options is very robust. Figure 4-5 shows that the majority of the calculated $\Delta NPV_{(p-f)}$ is positive, indicating pipe enlargement outperforms local infiltrations regardless of the uncertainties associated with the evaluation process, given that action should be taken. The uncertainty related to cost-recovery year of the two options also indicates that traditional pipe enlargement is preferable, although there is a low probability that local infiltration may perform well, primarily if the net benefits become positive before reinvestments are needed.

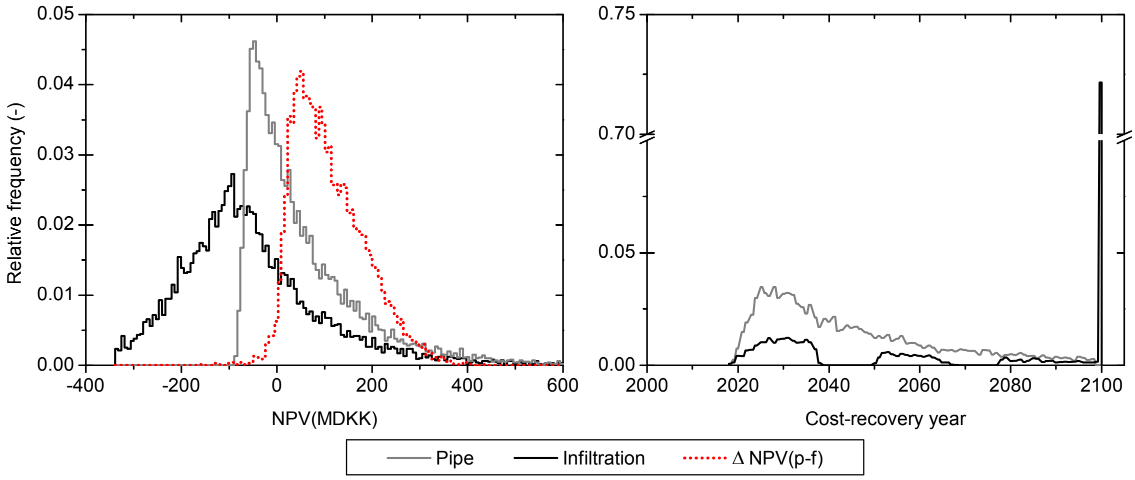

Figure 4-5: Calculated uncertainty ranges of individual net benefits, ΔNPV(P-F) and cost-recovery year of the two adaptation options, respectively. From Paper IV.

Figure 4-6 shows the results from the sensitivity analysis. It can be seen that for the NPV estimates comparing action to in-action, uncertainties associated with input runoff volume, threshold criteria, unit costs and discounting rate demonstrate the most significant influences. Climate factors and investment costs are relatively less important in this case study. Regarding the marginal uncertainty for comparing adaptation options, ΔNPV, the discount rate, investment costs and input runoff volume are found to be important for decision making whereas the other sources of uncertainty seems to be of less importance. This seems likely since the uncertainties related to costing of floods and climate impacts will be levelled out when comparing the options, thus also being the major reason for the reduced overall uncertainty. The influence of threshold criteria on ΔNPV depends to some extent on the area-depth uncertainties (input runoff volume); therefore this variable has some impacts on the uncertainty. For payback time the impacts of input variables are in general small. This is due to the high investment costs required in both scenarios and a high degree of non-linearity between the input uncertainty and the resulting calculated payback time, especially for the infiltration measure.

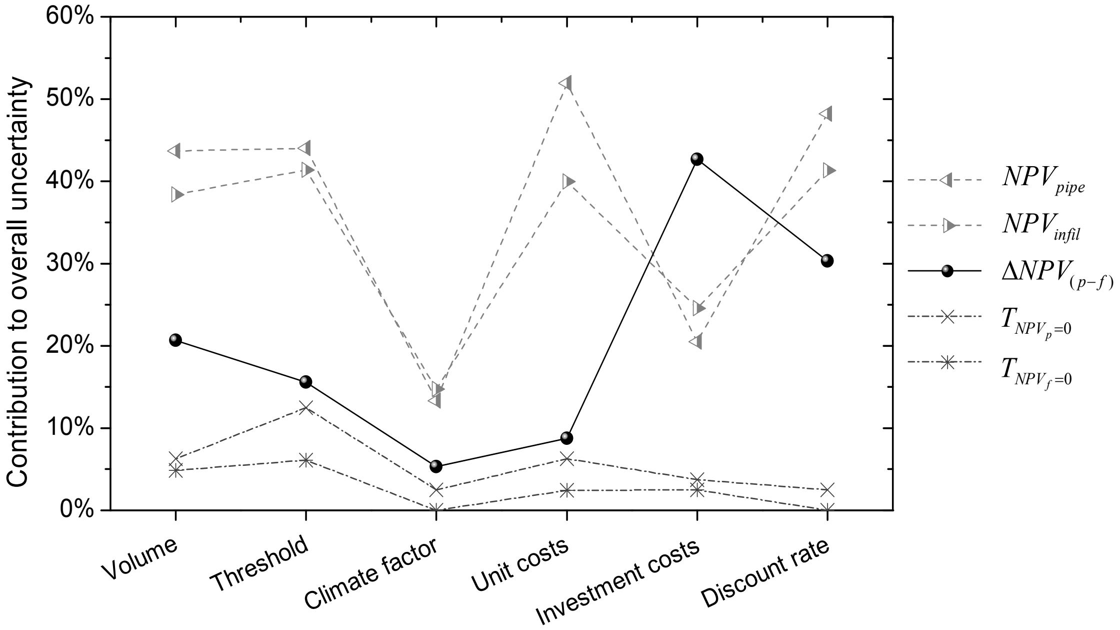

Figure 4-6: Relative contribution of input variables to the uncertainty of assessed indicators. From Paper IV.

The case study shows how to perform an integrated uncertainty analysis to quantify the overall and marginal uncertainties associated with climate adaptation assessment. The study shows that although uncertainties of climate adaptation assessment are in general high, it is still possible to choose a robust adaptation based on uncertainty assessment of appropriate evaluation indicators. The sensitivity analysis helps to identify and communicate the important sources of uncertainties in the evaluation, which can be used to guide further efforts on uncertainty reduction.

5. Reframing: including intangible goods in urban climate adaptation assessment

During different time periods urban drainage has been viewed with different perspectives and hence designed for different objectives. To facilitate the decision making on urban drainage design, Fratini et al. (2012) introduced three domains wherein water professionals may act and where aspects valued by different stakeholders come into play, see Figure 5-1. The first domain focuses on technical optimization of the system performance based on a design rainfall. This domain deals a lot with standards and guidelines for urban drainage design as well as economic optimization at the utility level. The second domain focuses on coping with extreme rainfalls, which has recently gained much attention due to climate change impacts. Adaptation is needed to upgrade the system and manage the increasing flood risk in a cost-effective way. The third domain represents daily rainfall, which was mainly perceived as nuisance in the past. Due to the rising of the water sensitive urban design (WSUD) concept, there is an increasing tendency to look at the stormwater as a positive resource in the urban landscape (Chocat et al., 2007; Stahre, 2006). This offers an opportunity and need to take into account the intangible day-to-day values (e.g. aesthetics, environmental amenities and recreational values) in the design of urban drainage.

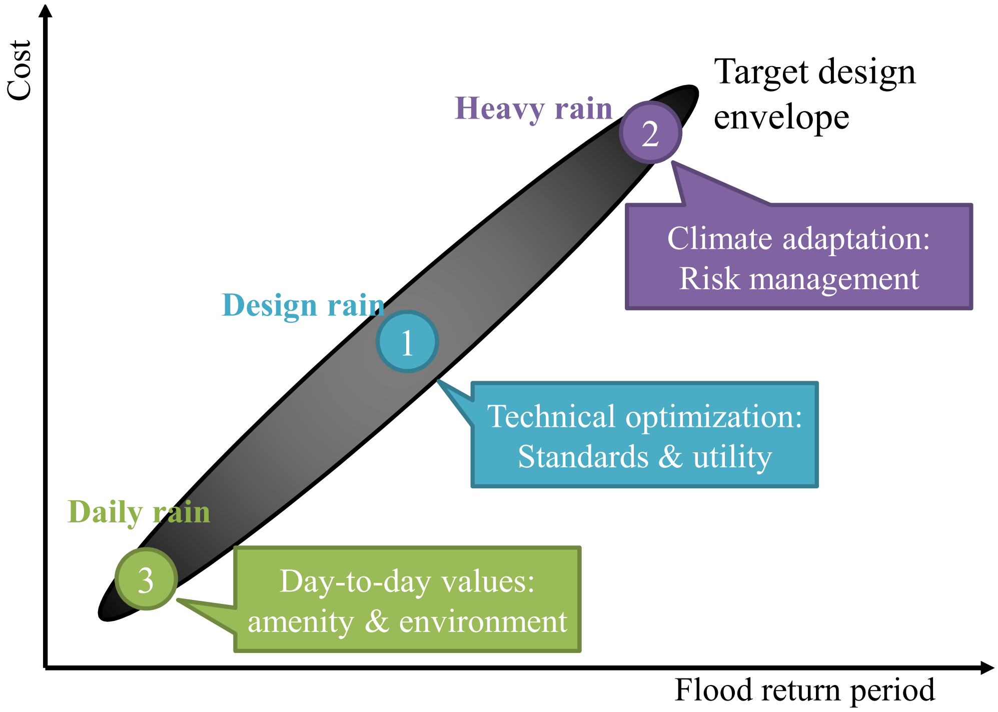

Figure 5-1: Three domains of urban drainage design, adapted from Fratini et al. (2012) and (Arnbjerg-Nielsen and Mikkelsen, 2009).

The term Water Sensitive Urban Design (WSUD) was first proposed by various Australian design professionals. WSUD refers to an approach to sustainably integrate water resource management into urban planning and design. Common WSUD practices are a combination of elements such as local treatment, attenuation, detention, re-use and infiltration of precipitation runoff (Ashley et al., 2007; BMT WBM, 2009; Roy et al., 2008). Terminologies of similar design philosophies vary in the world. Examples of other terminologies for WSUD are Low Impact Development (LID) and Best Management Practices (BMP). WSUD is also known as Sustainable Urban Drainage System (SUDS) in northern Europe and UK (Stahre, 2006; Willems et al., 2012b). In Denmark, several major national research projects are looking into this issue, such as 'Water in urban areas', www.vandibyer.dk , and '2BG', www.2bg.dk.

One of the most characteristic features of such innovative solutions is to incorporate intangible goods (e.g. recreational amenities, social aspects) in the design of urban drainage. However, the traditional urban drainage design focuses mainly on the first two domains of the 3PA. This means the majority of the risk-based economic assessments only account for the response impacts within the context of hydrological extremes. In other words, there are a diversity of the day-to-day intangible values cannot be well reflected by the traditional engineering approach. Decision makers need appropriate technical and economic tools to react to the challenges and the traditional approach needs to be extended or reframed to incorporate the additional response impacts in the evaluation (Marsalek and Chocat, 2002; Wong and Eadie, 2000).

To achieve an appropriate framing of climate change adaptation assessment (e.g. what kinds of response impacts should be taken into account?), this chapter studies the impacts of the framing uncertainty (see Chapter 4.1) on adaptation assessment. First of all, a reframed approach is introduced to include evaluation of added intangible values of adaptation measures, by means of incorporating different economic valuation techniques in the risk-based framework. Next, a case study is applied to show the feasibility of the new approach and compare the difference in achieved results obtained from the traditional and reframed approaches.

5.1 The multiple-disciplinary framework for climate adaptation assessment

Figure 5-2 shows the general procedure of the multiple-disciplinary framework. The framework is built on the aforementioned risk-based economic analysis for evaluating costs and benefits within the traditional CBA context, but is further extended by adding a new component for assessing the additional intangible values of adaptation measures by economic valuation models. It can be seen that in total there are four components in the framework: the adaptation scheme describes the anticipated climate change impacts in an area as well as the planned adaptation alternatives in response to the change. The flood risk analysis is performed based on the flood risk assessment framework estimating hazard and vulnerability characteristics of the area under the investigated adaptation strategy. Economic valuation of flood risk reduction in the hydrological context is assessed using the socio-economic framework to aggregate the gross benefits and costs of the adaptation strategy. Finally, economic valuation models are applied to capture the added environmental, socio and recreational values related to the adaptation measures.

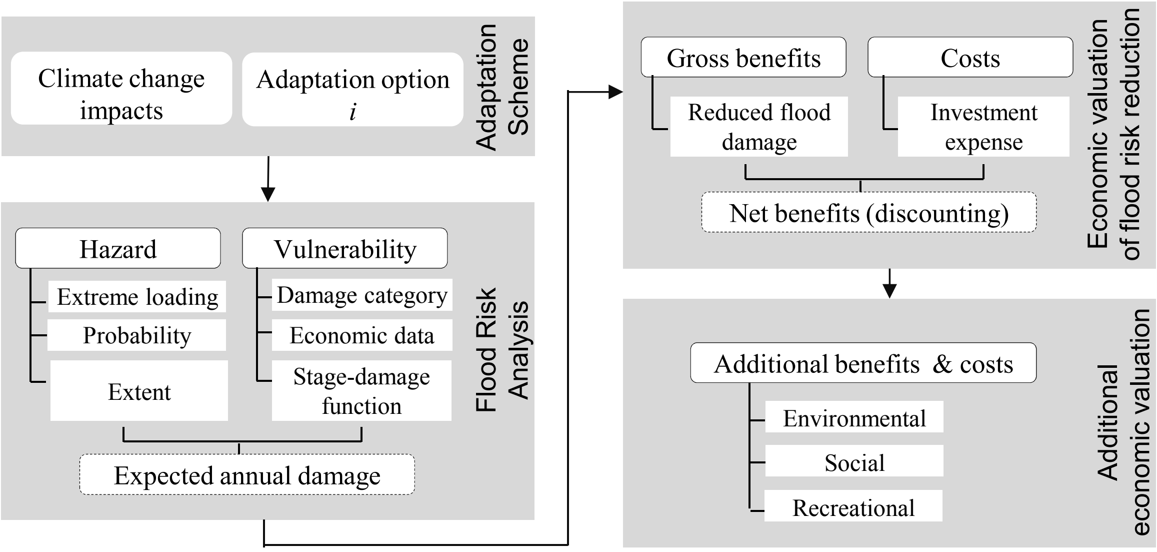

Figure 5-2: An overview of the reframed framework. The risk-based economic framework focuses on assessing response impacts in the first two domains of 3PA and the additional economic valuation component accounts for the intangible values in the third domain. Adapted from Paper V.

Various additional response impacts need to be considered in the adaptation assessment. For instance, the aforementioned recreational amenities due to nice blue–green neighbourhoods from some of the water sensitive urban design

(Stahre, 2006; Wong and Eadie, 2000). Adaptation measures may also bring additional environmental impacts, such as reduced groundwater pollution, increased combined sewer overflows (CSO), and threats to aquatic habitats (Floodsite, 2009; Gautam and van der Hoek, 2003). The costs and /or benefits of these additional impacts cannot be found directly in the market and therefore appropriate tools are necessary to reflect their underlying values.

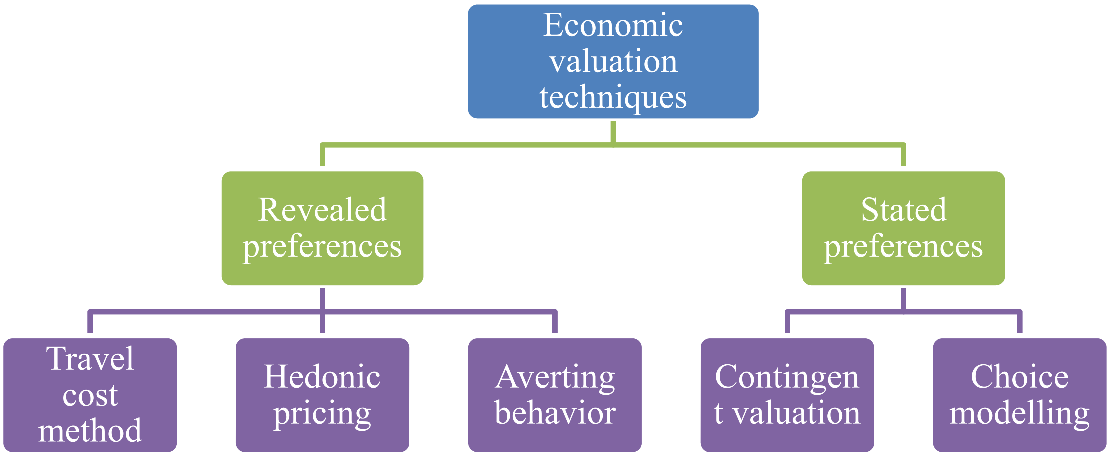

Figure 5-3: An overview of economic valuation techniques for assessing additional response impacts of adaptation measures.

There are a number of economic valuation techniques to measure the added intangible values due to adaptation measures, see Figure 5-3. Revealed preference techniques (RP) seek to reflect the economic value of an intangible good or service by capturing the behaviour trail or purchasing habits of consumers in the market for the related good (Bateman et al., 2002). RP include a range of methods based on different conceptual bases. For example, the travel cost method reveals the ‘price’ of an intangible good (e.g. service, impact, recreational value) by utilizing information of the time and travel costs that people spent to access the good (Fix and Loomis, 1997; Pearce et al., 2006). Hedonic pricing method utilizes the fact that the pricing of a market good is influenced by its characteristics (Pearce et al., 2006). For example, the price of a house is determined not only by the characteristics of the house itself (e.g. size, condition), but also by its intangible characteristics/goods (e.g. proximity to a recreational site, risk of flooding, level of air pollution). Such intangible values can be reflected by using statistical analysis of market transactions of the good (Bateman et al., 2002; Pearce et al., 2006; Ready et al., 1997; Taylor, 2003).

Averting behaviour method is commonly applied to reveal the value of negative intangible impacts, e.g. water pollution, health risk. The method is to analyse what individuals do in order to protect them against the negative intangible impacts (Abdalla et al., 1992; Um et al., 2002).

Stated preference techniques (SP) utilize survey-based techniques to uncover the underlying value of an intangible good from responses to hypothetical questions (Pearce et al., 2006). When using stated preference techniques, the main choice is between contingent valuation and choice modelling methods (Bateman et al., 2002). In the contingent valuation method (CVM) respondents are asked to state their preferences, in monetary terms, for changes in the quantity or quality of an intangible good or service. While in the choice modelling method (CMM) the respondents are asked to elicit their preferences for the attributes, or characteristics of the good. As a result, the CVM is more applicable when the total value of an intangible good/impact is needed while CMM should be used if information on relative values of different attribute of a good is needed (Bateman et al., 2002; Bennett and Blamey, 2001; Pearce et al., 2006).

By using the economic valuation methods, it is possible to evaluate the socio-economic values of the additional intangible impacts due to implementation of adaptation measures. This provides important tools for assessing benefits and costs of urban drainage adaptation projects when a broader perspective is considered in a cross-disciplinary context.

5.2 Case study

We apply the reframed approach for analysis of four adaptation strategies in the catchment of Risskov, Denmark. Besides the economic analysis of flood risk reduction in the hydrological context, the additional recreational amenities of the adaptation alternatives are taken into account. This is done by using a cost benefit analysis that included a hedonic valuation of economic gains or losses from the adaptation design in the area.

5.2.1 Area description and planned adaptation measures

The catchment of Risskov is located in the northern part of the center of Aarhus city, see Figure 5-4. It is one of the wealthiest residential areas in Aarhus with high property values. There are only few commercial and industrial activities in the area. It can be seen that Risskov has widespread green spaces and therefore has a great potential for decentralized drainage constructions. The area is served by a separate sewer system conveying storm water from west to the outlets along the eastern coastline. More details on the catchment can be found in Paper V.

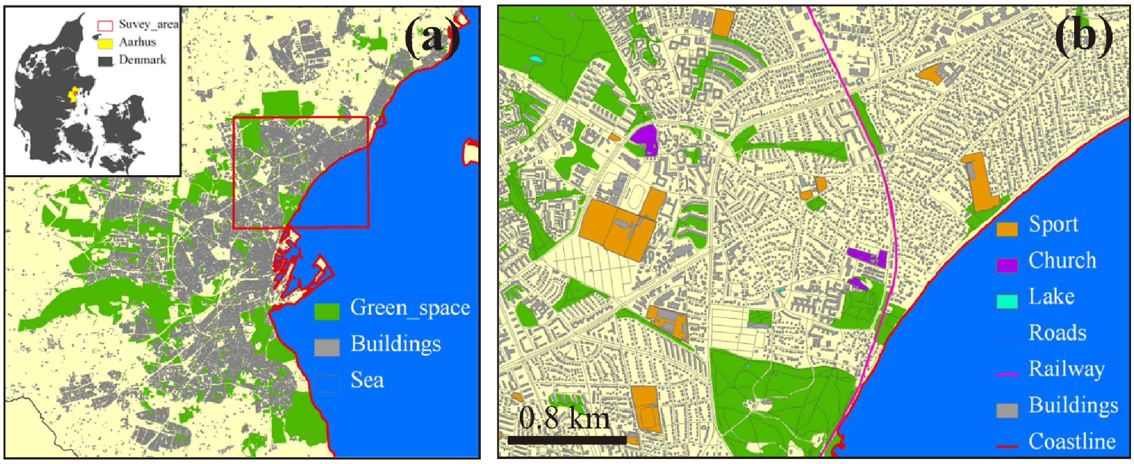

Figure 5-4: (a) Location of Risskov and (b) a close overview of Risskov. From Paper V.

Four distinct adaptation strategies are investigated for climate adaptation. The first is a laissez-faire strategy, which assumes that urban storm water is to be handled by existing drainage only. The second is a business-as-usual (BAU) strategy, pipe enlargement, which assumes that increased drainage capacity is obtained by means of expansion of sewer pipes and concrete rainwater basins when necessary. The third strategy, the infiltration strategy, uses household-scale underground infiltration units that local property owners can implement on their own properties. Such systems will go unnoticed to the public eye and therefore do not provide additional recreational benefits. The fourth is the recreational open basin strategy (ROB), an open urban drainage system integrating rainwater basins in pleasant green areas to provide additional recreational benefits. Further details on the applied four adaptation strategies see Paper V.

5.2.2 The hedonic house price valuation

Among the various valuation techniques, hedonic house price method is most often used to evaluate the welfare economic values of environmental amenities that affect the price of residential properties. The method provides a more credible and justified assessment of the recreational values implied by the recreational open basin strategy, based on the actual observed house price data in the market.

In this study, house price is described as a function of both construction characteristics (such as property size, property age, roof material, size of garden, number of toilets and size of basement) and neighbourhood characteristics (such as distance to city center, distance to sport facility, size of nearby recreational site, accessibility of a lake, distance to main road). To identify the impacts of variables describing recreational amenities (e.g. size of a lake, accessibility to green area with tree cover) on house price, a control variable is used to capture and summarize the variance that is not related to the variables of interest. As a result, benefits of various types of green areas and the presence of water in the catchment can be distinguished and captured in the established hedonic model, see Paper V for more details.

5.2.3 Results

The results from the hedonic house price valuation show that three types of landuse are significant to the property prices in the catchment. The first type refers to a group of green areas that contain lakes and/or tree covers, respectively. It is found that an increase in the size of such green areas will have a positive influence on house prices. Furthermore, an increase in distance to such green areas will lead to decreases in house prices. The results show that urban green areas without lakes or tree covers affected the nearby properties negatively. The third type of landuse refers to lakes (including those not integrated in green areas) and it is found that there will be decreases in property prices due to increased distance to lakes.

For the Laissez-faire strategy, owing to climate change the EAD was estimated to increase from 8.3 to 17.8 MDKK from year 2011 to 2100. Figure 5-5 shows where measures are suggested for the tested adaptation strategies. With respect to pipe enlargement, in total 2636 meters of pipe is enlarged and an extra open basin is invested to handle a severe local flooding in the area. Regarding infiltration, in total 14.53 hectares impervious area had to be disconnected, corresponding to a roof area of 727 buildings (Figure 5-5b). For recreational open basin (ROB) strategy, it is estimated that in total 8 basins are needed in the area to cope with flood risks. Furthermore, we divided the strategy into two subscenarios: ROB 1 and ROB 2. In the ROB 1 we assume that the five basins located on private properties will take up parts of the garden of the property. Three basins are located within existing green space, which will be constructed as the recreational lakes in the area. In the ROB 2 we assume that properties affected by rainwater basins in ROB 1 are converted into green spaces with smaller permanent lakes. Two of the affected areas are too small to be considered as green spaces and will therefore still be categorized as rainwater basins with no hedonic effects. In total 3450 properties are affected by the changes in ROB 1 and ROB 2.

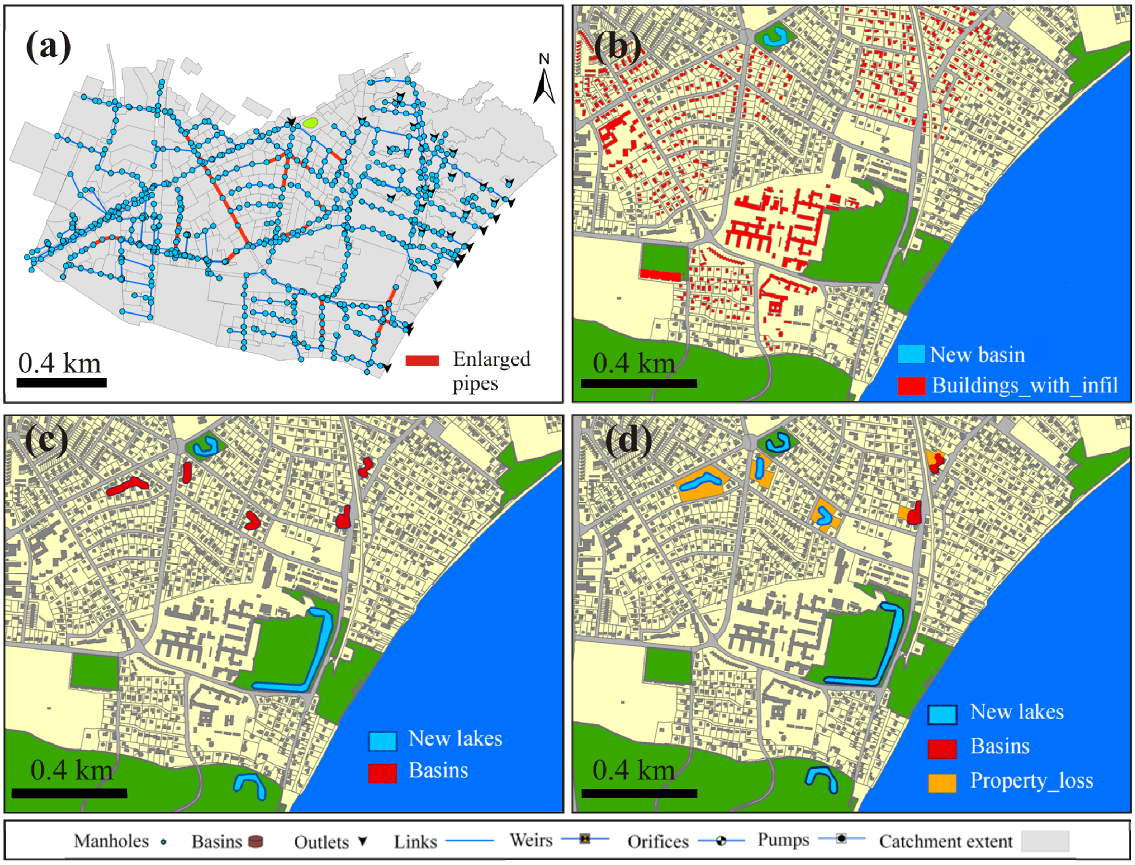

Figure 5-5: Illustration of (a) pipe enlargement, (b) infiltration, (c) ROB 1 and (d) ROB 2. The figures show where measures are suggested for tested adaptation scenarios based on an optimization of costs and benefits. From Paper V.

Table 5-1 shows the costs and benefits estimated using the traditional and reframed framework, respectively. It can be seen that based on the traditional framework, the calculated NPVs (NPV1) of all investigated adaptation strategies are positive relative to the laissez-faire strategy. This implies that it is economically beneficial to adapt to climate change in the area. Local infiltration achieves the largest reduction in the EAD, however, the solution turned out to be less cost-beneficial due to its large investment costs. Pipe enlargement and recreational open basins are almost equally good in terms of flood risk reduction. Nevertheless, when reframing the analysis to include additional recreational amenity effects, there is a considerable increase in estimated NPV of the recreational open basin strategy. The hedonic valuation results show that ROB 1 and ROB 2 respectively provide a potential increase of 400 and 276 MDKK in NPV, which accounted for the increase in property tax due to changes in environmental amenity, see Paper V for more details. As a result, the recreational open basin strategy turns out to be the best solution of the options considered.

Table 5-1: Estimated reductions in expected annual damages assuming climate change (CC), as well as the total investment costs demanded for the four adaptation strategies. Note that the investment costs are calculated in NPV with a discount rate of 3 % for a 100-year horizon. The NPV1 and NPV2 denote the calculated net benefits from the conventional and reframed CBA, respectively. Adapted from Paper V.

	Traditional CBA		Hedonic valuation		
	EAD	Investment costs	Recreational effects	NPV1	NPV2
Laissez-faire	17.8	0	0	- 93	-93
Pipe enlargement	8.37	24.07	0	147	147
Local infiltration	4.63	87.12*	0	111	111
ROB 1	6.25	54.50*	400	157	557
ROB 2			276		433

*: Three investments were assumed needed over the planning horizon

The study shows that climate change adaptation based on the traditional engineering solutions might be a suboptimal approach for decision making as it overlooks the additional response impacts linked with adaptation measures. The reframed framework is especially important and suitable for complex evaluations where a broader perspective is considered. By integrating different economic valuation techniques, it is possible to quantify various additional intangible impacts in a qualitative manner for cost benefit analysis.

6. Discussions

Urban drainage has played an essential role in managing flood protection, public health and safety, as well as environmental protection in cities. This thesis focuses on the element of flood protection and aims to identify new principles of urban drainage design under the influence of climate change impacts. An integrated and systemic framework is introduced to guide adaptation strategies in a cost-effective manner. The value and feasibility of the framework is tested in two Danish case studies and the overall results show that the framework has a high potential to complement current design practices of urban drainage in response to the increasing flood risk due to climate change. However, it is also necessary to note that the studies performed in the thesis are based on several assumptions, which may influence the results in different contexts. To provide more insights on the results and conclusions of the thesis, some of the important assumptions are discussed below.

The setup of applied adaptation options has been simplified in terms of model simulation and economic assessment. For instance, when calculating the investment costs for pipe enlargement full construction costs are utilized in the study. This may lead to a significant overestimation of the total investment costs since in many cases only replacement costs of pipe enlargement are needed, which merely correspond to a small proportion of the full construction costs. Local infiltration is modelled by directly reducing the imperviousness of subcatchments, which simplifies the hydrological response process of infiltration and ignores the actual context of the area (Brander et al., 2004; Chen et al., 2009; Diskin and Nazimov, 1995). For instance, in practice local infiltration may to a great extent encounter challenges due to e.g. limited space, unsuitable soil conditions, ground water pollution issue, and instability of buildings. Neglecting such practical details in modelling will overvalue the potential of the measure and hence the actual economic benefits are likely to be lower than expected. Construction of recreational open basins in the model is performed by creating local depressions as well as flow paths conveying water runoffs towards the basins. The locations of the basins and the flow paths may not be appropriate in reality owing to e.g. legislation limitations and geographic restrictions. Knowledge on the operation and maintenance (O&M) of the system is also very limited. Therefore the technical functionality of the measure has not yet been studied to ensure the system can perform as well as natural systems. In addition, the indirect costs and benefits of the applied options due to additional environmental impacts (e.g. water quality) are not taken into account in the economic analysis. Adding such indirect intangible values in the framework may further influence the decision making.

The collection of data is an essential and tough step in the economic analysis to provide information on costing of damage and adaptation solutions. Due to limitations of time and resources, it was not possible to conduct an original field valuation study for the various damage categories and options in the study. As a result, the data used for the economic assessment are obtained from literature review of relevant Danish case studies by research institutes, municipalities, utility companies and/or private companies. Most of the data are regionally aggregated and/or transferred from meso analysis carried out at a larger scale. Some damage data are assessed based on expert consultation. Certainly, we also note the large uncertainty associated with the applied data and future work has been planned to improve the data quality through collaborating with municipalities and insurance companies. Paper III shows a preliminary study we carried out to validate the hazard and vulnerability assessment of floods in a Danish catchment based on insurance data. The results show that by means of appropriate hazard modelling and GIS analysis, it is possible to identify the vulnerable properties in terms of their locations and flooded frequencies. With respect to vulnerability assessment, so far we are only able to establish a simple relationship between rainfall depth and daily aggregated costs. It remains a big challenge to model the variation in individual cost per claim.

It is important to know that the primary goal/value of the framework is to provide a decision making support tool to inform the efficiency of different adaptation alternatives, rather than determining the best solutions for decision makers. In reality, stakeholders may have different interests and preferences on adaptation solutions. That is to say, besides the technical and economic performance, it is important to include analysis of social feasibility of adaptation solutions in the decision making process. Difference in willingness to pay and perceived costs and benefits may be even more influential for actual decision making than the optimal solutions found using the risk-based cost-benefit framework.

Among the investigated adaptation solutions, pipe enlargement is more in line with the conventional public perceptions claiming that flood risk should be managed by municipalities and utilities in a centralized manner. In contrast, part of the reason that infiltration gains more popularity at the utility level is that most of the risks and costs lie with the private property owners under such a strategy. This implies a significant change in roles in the flood risk management process and may entail dissent voices from the householders. For example, scepticism may arise from the fact that the stakeholders to implement the solution do not benefit from the reduced risk of flooding and that they therefore may not be willing to reinvest in maintenance as required by the measure. Recreational open basins bring in additional recreational amenities in neighbourhoods and are in general favoured by public. It is mainly an action at the utility level; however, sometimes individual property owners are involved since the solution may take up their private spaces. It is important to find a common solution for all involved stakeholders and avoid conflicts with existing legislation and nature protection plans for the area. The individual assets protection requires active participation at the local level, which is still a questionable assumption in urban water management. A lot more resources and efforts are therefore needed from municipalities to communicate with the private households to realize the solution.

City development was not considered in the case studies as the analysed catchments are relatively small and well developed. Nevertheless, when assessing climate adaptation strategies, city development is an important driver of changes in the context of urban floods. Urban drainage system has quite a long technical service time and hence low flexibility coping with impacts due to the external driver. On the one hand, city development in terms of population growth, economic development and urbanization may lead to a significant increase in flood hazards and vulnerabilities. On the other hand, city development can improve the management of urban water infrastructure to reduce flood risk by means of better spatial planning, enhanced system resilience and promoted cross-sector coordination. Information on evolution of urban environment including land use, population, building types, water infrastructures is essential to take into account when making strategies for climate change adaptation in most contexts.

It is noteworthy that framing is very important for climate change adaptation assessment. The results may change significantly when different response impacts are incorporated in the assessment. As shown in the case studies, although uncertainties have been taken into account, adaptation strategies based on the traditional framing approach are still rather robust (see Chapter 3 and 4). When reframing the framework by including intangible response impacts, differences in economic efficiency between the two comparable solutions (pipe enlargement and Recreational Open Basins in Chapter 5) become substantial. The case studies also highlight the difficulties in setting up a proper framework for analysis. An appropriate stakeholder analysis and effective communication with decision makers can help to draw out the important response impacts to consider in the context in question and understand the uncertainties associated.

The economic estimation indicates that the water sensitive urban drainage design, such as the recreational open basins applied in the study, may be more economically beneficial when accounting for additional environmental and amenity benefits. Nevertheless, in reality, the implementation of such innovative measures is very likely to confront challenges as a result of e.g. technical constrains, policy failure, institutional barriers, stakeholder dissatisfaction and disbelief in assumptions. Therefore, when implementing innovative drainage solutions it is necessary to pay more attention on the complexity and practical characters of projects at the local scale.

The case studies carried out in the PhD project are mainly aimed at illustrating the feasibility of the introduced frameworks. Although the results and conclusions drawn from the case studies may give limited insights of analysed solutions due to applied simplifications and assumptions, the frameworks is feasible to serve as a guideline on climate adaptation design for urban drainage engineers.

7. Conclusions

Climate change presents a challenge to urban drainage as the system is one of the most expensive and inflexible types of infrastructure to adapt. Through the PhD thesis a systemic and integrated analysis of climate change adaptation have been introduced.

It is shown that the risk-based framework incorporating advanced flood inundation modelling and socio-economic tools can provide a quantitative understanding of the risks of different return periods and the negative impacts of climate change. In addition, the developed framework has the capacity to quantify the costs and benefits associated with different adaptation alternatives, thus enabling an evaluation of economic efficiency of adaptation measures and a prioritization of adaptation responses under the influence of climate change.

The thesis shows that uncertainty assessment of climate change adaptation options can be carried out by integrating Monte Carlo techniques in the risk-based economic framework. Such an approach allows an identification of a robust adaptation in situations of uncertainty, based on estimations of overall and marginal uncertainties of climate adaptation assessment. Equally important, the incorporated sensitivity analysis provides a better understanding of the roles and impacts of inherent uncertainties in the assessment. This helps to guide further research efforts to cope with and/or reduce the uncertainty propagation throughout the assessment.

It is shown that although uncertainty assessment of climate change adaptation is performed, the results obtained based on the traditional engineering solutions are rather robust. This indicates a need to study the impacts of location uncertainty on climate adaptation assessment. The thesis describes how to include intangible values of adaptation options in the climate adaptation assessment using a reframed design approach. It is feasible to assess the amenity values of water sensitive design solutions by incorporating different valuation techniques in the risk-based economic framework. The reframing is especially necessary when taking into account new aspects or values (e.g. amenity) in the design of urban drainage adaptation. The reframed approach is suggested as a support tool for decision making on climate adaptation when such a broader perspective is considered.

To summarize, the introduced framework incorporated with climate change, flood inundation modelling, socio-economic tools, environmental evaluation techniques and uncertainty analysis, can be used to improve the decision making on urban drainage adaptation assessment. The framework covers not only the traditional framing of urban drainage design, but also a broader perspective when added values of adaptation measures are included.

8. Suggestions for future research

It is essential to incorporate effects of city development in the planning and design of urban drainage adaptation. Future work is planned to study the long-term impacts of development of urban environment (e.g. population growth, land use change, evolution of city infrastructure, economy) on the risk level of flooding. Information on spatial distribution of flood risk, taking into account the presence of city development, can help decision makers to reduce the current and future vulnerability to floods, thus improving the decision making on climate change adaptation.

Secondly, the PhD study focused only on pluvial flooding in the urban context. In reality, especially in coastal or fluvial regions, concurrent hazards can be expected and the anticipated flood damage may be much higher than the one for an individual hazard. This may significantly influence the formulation of adaptation strategies as larger flood risk reduction and higher system flexibility are desired to cope with the concurrent events. It is of interest to undertake an examination of the combined effects due to the joint hazards on climate adaptation design in terms of both technical and economic performances. This can help to improve the original one-dimensional design framework on climate adaptation by incorporating the multi-dimensional hazard impacts.

In the chapter of uncertainty assessment a number of assumptions and simplifications are used since the applied models (e.g. Mike Urban for flood hazard modelling and GIS for damage identification and quantification) demand heavy computation. More importantly, we have not yet found a way to couple and link the various models applied in the framework, which means that the input and output of each model cannot be automatically transferred to other models for further analysis. As a result, it is quite time consuming to analyse adaptation alternatives by manually operating and coupling each model in the integrated framework. To optimize the analysis process, a common platform is necessary to facilitate the dynamic coupling and interaction between different models, see Figure 8-1.

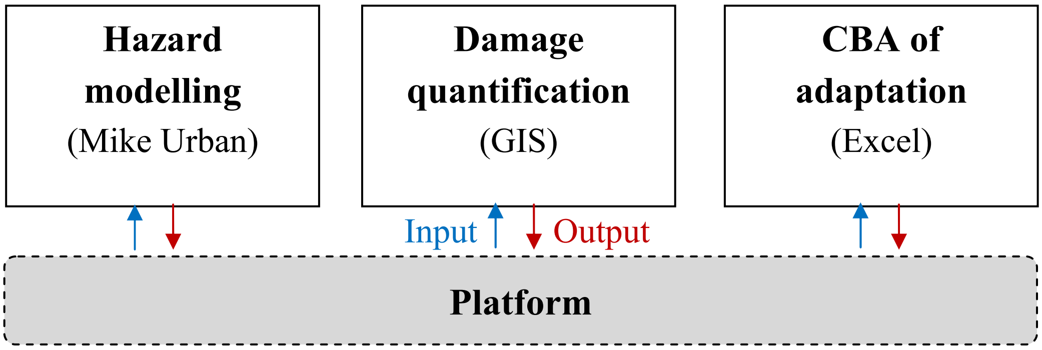

Figure 8-1: An example of iIllustration of a comon platform for various models in the integrated framework and the tools currently used to perform the calculations.

Traditionally, the modelling of urban drainage, groundwater and water supply has been managed separately. Nowadays, due to the rise of water sensitive urban drainage solutions (e.g. infiltration, rainfall harvesting), there are more interactions or conflicts among the different water resources when implementing adaptation solutions. For instance, when applying local infiltration the groundwater table level may strongly limit the infiltration capacity. Moreover, rainfall harvesting can be used to reduce the hydrological load to urban drainage systems during precipitation events, but it also be applied as an alternative water supply for households. To enhance the synergy between urban drainage adaptation and water resources management, an integrated modelling of various water impacts is suggested to have a better understanding of their interactive effects.

The thesis shows that the actual flood risk is often dominated by ‘high probability/low damage’ events (Merz et al., 2009), which may differ significantly with the perceived risk by public. From a societal point of view, in contrast, the very extreme events (low probability/high damage) are more important to cope with, even though their contributions to the overall risk are small. It is of interest to study the impacts of the disagreement between the actual and perceived risks on decisions on climate adaptation. Relevant tools (e.g. MCA) can be incorporated to take into account societal priorities/public preferences in the assessment of adaptation options.

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10. Papers

I. Zhou, Q., Mikkelsen, P. S., Halsnæs, K., Arnbjerg-Nielsen, K. (2012). *Framework for economic pluvial flood risk assessment considering climate change effects and adaptation benefits*. Journal of Hydrology, 414–415(0), 539-549.

II. Zhou, Q., Halsnæs, K., Arnbjerg-Nielsen, K. *Economic assessment of climate adaptation options for urban drainage design in Odense, Denmark*. Water Science and Technology, 66(8), 1812-1820.

III. Zhou, Q., Panduro, T. E., Thorsen, B. J., Arnbjerg-Nielsen, K. *Verification of flood damage modeling using insurance data*. The 9th International Conference on Urban Drainage Modelling, Belgrade, Serbia, 4 -7 September 2012.

IV. Zhou, Q., Arnbjerg-Nielsen, K. *Uncertainty assessment of climate change adaptation options using an economic pluvial flood risk framework*. Submitted manuscript.

V. Zhou, Q., Panduro, T. E., Thorsen, B. J., Arnbjerg-Nielsen, K. *Adaption to extreme rainfall with open urban drainage system – An integrated hydrological cost benefit analysis*. Submitted manuscript.

The papers **I-V** are included in the printed version of the thesis but not in the www-version.
Copies of the papers can be obtained from the
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ISBN 978-87-92654-80-9