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PhD Thesis
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Preface

The thesis is organized in two parts: the first part puts into context the findings of the PhD in an introductive review; the second part consists of the papers listed below. These will be referred to in the text by their paper number written with the Roman numerals **I-IV**.

I H. Åström, P. Friis Hansen, L. Garré, K. Arnbjerg-Nielsen, 2014. *An influence diagram for urban flood risk assessment through pluvial flood hazards under non-stationary conditions*. Journal of Water and Climate Change, 5 (3), pp. 276-286. doi:10.2166/wcc.2014.103

II H. Åström, M. Sunyer, H. Madsen, D. Rosbjerg, K. Arnbjerg-Nielsen. *Explanatory analysis of the relationship between atmospheric circulation and flood generating events in a coastal city.* Manuscript in Review (Hydrological Processes)

III J. Gregg, H. Åström, P. Skougaard Kaspersen, Q. Zhou, L. Garré, M. Drews, K. Halsnæs, K. Arnbjerg-Nielsen. *Urban Flood risk and adaptation management using Bayesian Influence Diagrams.* Manuscript in preparation

IV H. Åström, H. Madsen, P. Friis Hansen, D. Rosbjerg, K. Arnbjerg-Nielsen. *A spatially distributed and non-stationary urban flood risk assessment methodology for multiple hazards using a Bayesian Influence diagram.* Submitted manuscript (Journal of Hydrology)

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

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I also wish to thank all my friends that have supported me through the years. All you in Copenhagen who has made my years here in Denmark amazing, all my good friends from back home who have always been just a phone call away, and all you other friends from all around the world, which I always look forward to seeing again. Many thanks for being where you are and doing what you do.

I want to thank my family back home; Seija, Pappa, Hanna, Miro, Roxi, Thomas, Putte, and Hyunjee. They have given so much support and always showed interest in my wellbeing and my work. Finally, I want to thank my two favorite men, Morten and Charlie, who always seems to be in the right place, at the right time.

Summary

Flooding is one of the most damaging natural hazards to human societies. Recent decades have shown that flooding constitutes major threats worldwide, and due to anticipated climate change the occurrence of damaging flood events is expected to increase. Urban areas are especially vulnerable to flooding, because these areas comprise large amounts of valuable assets. Flooding in urban areas can grow into significant disruptions and national threats unless appropriate flood risk management (FRM) plans are developed and timely adaptation options are implemented.

FRM is a well-established process that aims to keep flood risk at, or reduce flood risk to, an acceptable level in flood prone areas. According to IPCC's Summary for policy-makers (2014), risk management is an iterative process that is divided into 3 phases, which in this thesis are adapted to fit FRM terminology. Hence, FRM includes flood risk scoping, flood risk assessment (FRA), and adaptation implementation and involves an ongoing process of assessment, reassessment, and response.

This thesis mainly focuses on the FRA phase of FRM. FRA includes hazard analysis and impact assessment (combined called a risk analysis), adaptation identification and adaptation assessment. The main task of FRA is to combine these assessments in a robust and systematic manner to provide valuable information to decision-makers by identifying suitable adaptation options and developing feasible adaptation strategies.

In this study, a FRA method using the Bayesian Network (BN) approach is developed, and the method is exemplified in an urban catchment. BNs have become an increasingly popular method for describing complex systems and aiding decision-making under uncertainty. In environmental management, BNs have mainly been utilized in ecological assessments and water resources management studies, whereas climate risk studies have not yet fully adapted the BN method. A BN is a graphical model that utilizes causal relationships to describe the overall system where risk occurs. A BN can be further extended into a Bayesian Influence diagram (ID) by including decision and utility nodes, which are beneficial in decision-making problems.

This thesis aims at addressing four specific challenges identified in FRA and showing how these challenges may be addressed using an ID. Firstly, this thesis presents how an ID can be utilized to describe the temporal dimension of flood risk in a coherent and systematic manner. Herein, risk is assessed in

so called time slices, where each time slice represents one specific year. For each time slice, separate hazard analyses are conducted to assess the occurrence probability of hazards in that specific year. Time slices are connected with each other by connecting the adaptation nodes in the time slices.

Secondly, this thesis recognizes the need for including a spatial dimension in FRA. An urban catchment is rarely homogenous, and there are areas that have a higher risk than others. From a decision-making point of view, a spatial risk profile may provide valuable insight in where risk is higher than acceptable and where additional adaptation measures are needed to keep risk at an acceptable level. In an ID, the urban catchment can be divided into sub-regions, and risk is described for each sub-region separately.

Thirdly, the objective is to improve FRA by including multiple hazards caused by concurrent events. Concurrent events refer to two or more flood hazards that occur simultaneously. In such circumstances the hazards may interact, and total damage from such a concurrent event may be larger than for the hazards separately. Currently, FRA is mainly based on single hazard events, but with expected climate change impacts there may be a need to include several hazards into FRA to assure that risk is described correctly for identification of important adaptation. This thesis shows that IDs may serve as a good approach for inclusion of multiple hazards in FRAs.

Lastly, the inclusion of multiple hazards in FRA may be challenging, among others because concurrent events are rare. However, with climate change, the annual variation of hazards may change, and concurrent events may become more frequent. Large-scale atmospheric circulation influences local and regional climate and is considered an important factor when aiming at improving our understanding of local weather conditions and the occurrence of extreme events. Hence, this thesis presents a study that explores the relationship between flood generating hazards and large-scale atmospheric circulation.

This thesis concludes that IDs can serve as a good approach for describing the complex system in which flood risk occurs. The final product is a spatio-temporal FRA approach that can include the impacts from multiple hazards.

Dansk sammenfatning

Oversvømmelser hører til blandt de mest ødelæggende naturkatastrofer i dagens samfund. De seneste årtier har vist, at oversvømmelser udgør en væsentlig trussel verden over, og grundet de forventede klimaforandringer forventes en forøgelses i antallet og størrelsen af skadevoldende oversvømmelser. Urbane områder er særligt udsatte på grund af de mange værdier i byerne, såsom bebyggelse og infrastruktur. Oversvømmelser i urbane områder kan forårsage væsentlige sammenbrud og nationale trusler, såfremt der ikke udarbejdes realistiske oversvømmelses- og risikoplaner (*flood risk management, FRM)*, og den nødvendige tilpasning ikke gennemføres med rettidig omhu.

FRM er en veletableret proces, der sigter mod at bevare eller etablere et acceptabelt niveau for oversvømmelsesrisikoen i udsatte områder. Ifølge IPCC, *Summary for policy-makers* (2014), er risikostyring en iterativ proces, der er opbygget i tre faser, som i denne afhandling er tilpasset til FRM-terminologien. Således omhandler FRM en identifikation af oversvømmelsesrisiko, oversvømmelsesrisikovurdering (*flood risk assesment,* FRA) og -tilpasning og omfatter desuden en fortløbende proces med vurdering, revurdering og respons.

Det primære fokus for denne afhandling er FRA-fasen af FRM. FRA omfatter årsags- og konsekvensanalyse (samlet kaldet risikoanalyse), samt identifikation og vurdering af tilpasning. Hovedformål med FRA er at skabe en samlet risikovurdering på en robust og systematisk måde for derved at bidrage med værdifuld information til beslutningstagere i forhold til at identificere egnede tilpasningsmuligheder og udvikle robuste tilpasningsstrategier.

Der er i dette arbejdet udviklet en metode, der bygger på Baysianske Netværk (BN), og metoden eksemplificeres i et urbant opland. BN er blevet en populær metode til at beskrive komplekse systemer og til at støtte beslutningsprocesser. I miljøforvaltning er BN hovedsagligt blevet benyttet indenfor økologiske vurderinger og vandressourceplanlægning. Derimod er BN indtil nu kun sjældent anvendt til vurdering af klimarelaterede risici. Et BN er en grafisk model, der benytter kausale forhold til at beskrive det system, hvori risikoen opstår. Et BN kan yderligere udvides til et Influens Diagram (ID) ved at medtage beslutnings- og nytteknuder, der bruges under beslutningsprocessen.

Formålet med denne afhandling er at adressere fire specifikke udfordringer indenfor FRA og at vise, hvordan disse udfordringer kunne håndteres bedre ved brug af ID. Som det første præsenteres, hvorledes et ID kan anvendes til

at beskrive den tidslige dimension i oversvømmelsesrisiko på en sammenhørende og systematisk måde. Her benyttes de såkaldte tidsskiver (*time slices*), hvor hver tidsskive repræsenterer et specifikt år. For hver tidsskive fortages en separat vurdering af sandsynligheden af de enkelte hændelser for det specifikke år. Tidsskiverne er forbundet gennem tilpasningsknuderne i de enkelte skiver.

Som det andet påpeger denne afhandling, at der er behov for indregning af den geografiske dimension (*spatial*) i FRA. Et urbant opland er sjældent homogent, og der er områder, der har højere risiko end andre. Fra en beslutningstagers synspunkt kan den geografiske risikoprofil give værdifuld indsigt i, hvor risikoen er højere end acceptabelt, og hvor yderligere tilpasningsforanstaltninger er nødvendige for at risikoen holdes på et acceptabelt niveau. I en ID kan det urbane opland opdeles i delområder og risiko beskrives særskilt for hvert delområde.

Som det tredje er formålet at forbedre FRA ved at indarbejde flere årsager til oversvømmelser (*flood hazards*) i vurderingen inklusiv samtidige begivenheder. Samtidige begivenheder henviser til to eller flere årsager til oversvømmelser, der optræder samtidigt. I sådanne situationer kan den samlede skade være større end summen af de skader, som de enkelte årsager ville forårsage hver især. FRA er oftest baseret på vurdering af en enkelt årsag, men med de forventede klimaændringer kan der være behov for at inkludere flere årsager til oversvømmelser i FRA for at sikre, at risikoen er korrekt beskrevet til identifikation af den nødvendige tilpasning. Denne afhandling viser, at ID er en god tilgang til håndtering af multiple årsager i FRA.

Endeligt kan indregning af multiple årsager til oversvømmelse i FRA være udfordrende, blandt andet fordi samtidige hændelser er meget sjældne. Imidlertid kan klimaændringer ændre hyppigheden af samtidige hændelser. Storskala-atmosfærisk cirkulation (*Large-scale atmospheric circulation*) påvirker det regionale klima og betragtes som en væsentlig faktor for lokale vejrfænomener og forekomsten af ekstreme hændelser. Således præsenteres der i denne afhandling undersøgelser, der udforsker relationen mellem oversvømmelsesårsager og storskala atmosfærisk cirkulation.

Denne afhandling konkluderer, at IDer kan være en god måde at beskrivelse kompleksiteten omkring oversvømmelsesrisiko i urbane områder. Det endelige produkt er en spatial-temporal FRA metode, som kan medregne påvirkninger fra multiple årsager til oversvømmelse.

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Abbreviations

BN	Bayesian network
CBA	Cost-benefit analysis
CPT	Conditional probability table
CT	circulation type
DKK	Danish kronor
EAD	Expected annual damage
FRA	Flood risk assessment
FRM	Flood risk management
GCM	General circulation model
GDP	Gross domestic product
GIS	Geographical information system
ID	Influence diagram
IPCC	Intergovernmental panel on Climate Change
IRGC	International risk governance council
IWRM	Integrated water resources management
LCC	Lamb circulation class
LCT	Lamb circulation type
MCDA	Multi-criteria decision analysis
NPV	Net present value
PVC	Present value - cost
PDF	probability density function
PVB	Present value - benefits
RCM	Regional climate model
TAR	Third assessment report

1 Introduction

1.1 Flooding has a cost

Flooding is one of the most damaging natural hazards to human societies (Schanze, 2006; Wilby *et al.*, 2007), and recent decades have clearly shown that flooding constitutes a major threat worldwide. According to the EM-DAT (International Disaster database) by the Centre of Research on the Epidemiology of Disasters (CRED), Europe experienced 390 flood events in the period 1980-2008 with an estimated 2400 people killed and 77 million euros of damage (PreventionWeb, 2008). These flood events were spread out over entire Europe. For example in central Europe, flood events such as the Elbe flooding in 2002 resulted in approximately 15 billion euros of damage (Floodsite, 2009). The largest flooding in UK in modern history was reported in 2007 with an estimate of 6.5 billion euros of damage (Floodsite, 2009). In Denmark two major flood events were witnessed in 2010 and 2011 in Copenhagen (Copenhagen municipality, 2012). The 2011 flooding caused damage of approximately 5 billion DKK (670 million euros) (Shandana, 2012).

Urban environments have high concentrations of people and valuable assets (Walsh *et al.*, 2013). In Europe over 70% of the population lives in urban areas (GEOHIVE, 2010). As a result, urban areas are especially vulnerable to natural disasters, such as floods. Flooding in urban areas can grow into significant disruptions and national threats, unless feasible flood risk management (FRM) plans are developed and timely adaptation options are implemented (Hammond *et al.*, 2013).

1.2 Flood risk management to reduce losses

Flood risk management (FRM) is a well-established process for handling flood risks and for adapting areas at risk in an effort to reduce negative effects (Plate, 2002). The recognition of an upward trend in vulnerability to flooding in our societies and the potential impacts of climate change to flood occurrence (Hall & Solomatine, 2008) have led to an increased focus on FRM in recent years. In general, FRM refers to the entire process of dealing with flooding through keeping the risk at an acceptable level or decreasing the overall flood risk, thus accepting that flood risk can never be entirely avoided in our societies (Floodsite, 2009; Schanze, 2006).

Many FRM frameworks and approaches have been developed (Plate, 2002; Schanze, 2006; Floodsite, 2009; Willows & Connell, 2003; IPCC, 2014). This thesis applies the iterative risk management process from IPCC, Summary for policy makers, (2014) adapted from Willows & Connell (2003). The process is presented in Figure 1 in which the terminology is adapted to suit the FRM process according to Guidelines on Risk Assessment according to ANCOLD (The Australian National Committee on Large Dams) (ANCOLD, 2003). Accordingly, FRM is divided into three phases: scoping, assessment, and adaptation implementation, and involves an ongoing process of assessment, reassessment, and response (IRGC, 2005). This iterative process defines that different stages in FRM do not always follow one another, but that it may be necessary to return to previous steps to account for new options (Willows & Connell, 2003).

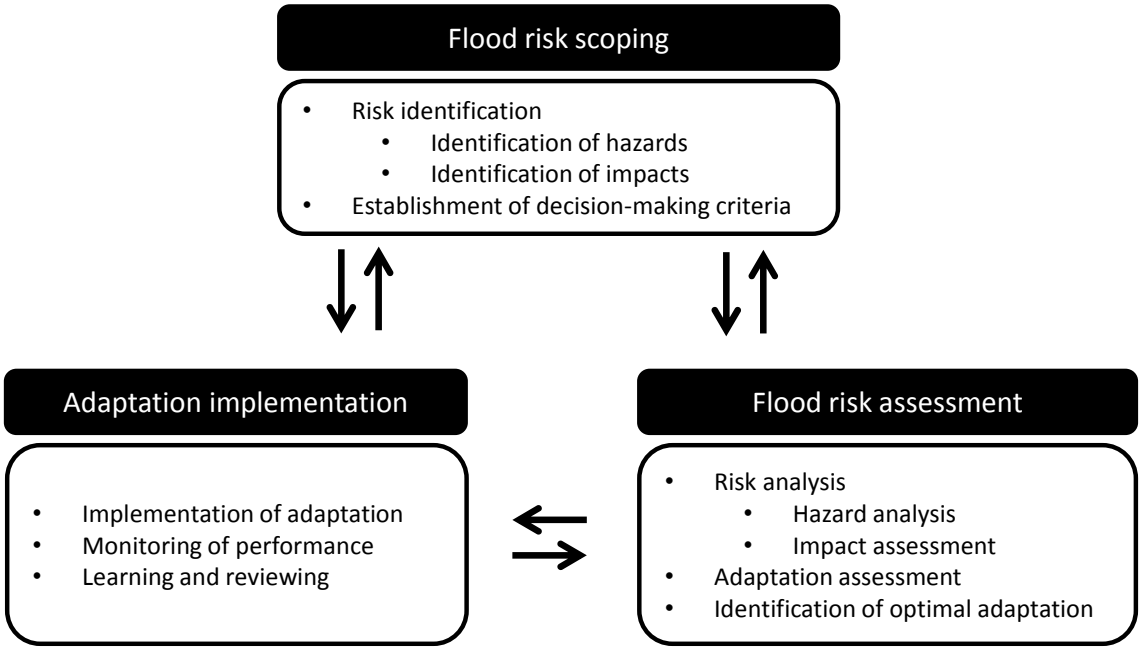


Figure 1. Iterative FRM approach adapted from IPCC Summary for policy makers (2014). The different steps do not necessarily follow one another as it may be necessary to return to previous steps to explore new options. The framework also recognizes that FRM is an ongoing process. Hence, after implementation of adaptation a new round of risk identification is conducted in order to constantly improve FRM.

Risk scoping includes *risk identification* that refers to the identification of hazards and consequences (impacts) that characterise flood risk. A range of hazards (extreme precipitation, high sea water levels, snowmelt etc.) may contribute to flood risk (Pedersen *et al*., 2012). Further, consequences may be presented by various economic, social, and ecological costs (Zhou *et al*., 2012). Based on the risk identification, *decision-criteria* are established. De-

cision-criteria are often economic in FRM, but also other decision criteria can be implemented (Meyer *et al*., 2009a).

The *flood risk assessment* (FRA) phase, firstly, involves *risk analysis* (Schanze, 2006; ANCOLD, 2003) that combines *hazard analysis* (defines the extent and probability of the hazard) and *impact assessment* (assessment of economic, social, and environmental negative effects).Change in risk over time is assessed by re-evaluating the probability of flood generating hazards and the impacts of these hazards in a future time period. The FRA phase also includes identification of adaptation measures (*adaptation identification*) and assessment of their positive effects (*adaptation assessment*). The adaptation assessment can be conducted using socio-economic assessments such as Cost-benefit analysis (CBA) (Zhou *et al*., 2012; Pearce *et al*., 2006) where decision criteria is defined as, for example, Net Present Value (NPV) or Benefit-Cost ratio, or Multiple Criteria Decision Analysis (MCDA) where multiple criteria with different units are utilized to describe the suitability of adaptation measures (Meyer *et al*., 2009b). The FRA phase ends with a decision on suitable adaptation. The *adaptation implementation* phase includes the actual implementation of adaptation together with monitoring of the performance and learning how to improve FRM further.

Each phase in the FRM framework is an interdisciplinary process. For example, the FRA part of the FRM process is to a large part based on expert approaches and methods (Plate, 2002) from various disciplines to describe the hazards, impacts and adaptation effects. However, the identification of adaptation measures is most often a political and societal issue, which requires that stakeholder preferences are paid attention to. Hence, practitioners in charge of decision-making interact with communities, stakeholders, and experts, and follow governmental guidelines on flood adaptation to define feasible adaptation actions to decrease damage (Morss *et al*., 2005; Adger *et al*., 2005). In addition, the final decision on which adaptation measure to implement is again a political task. FRM practitioners at many levels in the society have to weigh the different assessments, economic analyses, and stakeholder expectation and perceptions in order to reach a decision on how unacceptable flood damage should be tackled.

Consequently, FRM is by all means an interdisciplinary process with a wide range of scientists, engineers, practitioners and stakeholders involved and is as such a subject to several challenges (Levy, 2005; IRGC, 2005). The engineering community has an important role in developing FRA methods that

can easily be utilized to support the decision-making process in FRM. This requires developing improved methods to assess risk and adaptation benefits more accurately, and developing methods that can improve risk communication between the various stakeholders.

1.3 Problem formulation – 4 challenges in FRA

A wide range of scientific publications have presented FRA methods for various FRM issues (van Manen & Brinkhuis, 2003; Anselmo *et al.*, 1996; Reeve, 1998) with the aim of shifting flood management from old concepts such as "flood protection" and "flood defence" to risk-based methods (Meyer *et al.*, 2009b; Schanze, 2006).

More recently, the focus has been on improving the applicability of risk assessments into actual decision-making. Two approaches have been dominating: 1) a risk based economic framework for flood management, where risk is defined as Expected Annual Damage (EAD) and is used to assess benefits of adaptation measures in a CBA (Zhou *et al.*, 2012), and 2) a multi-criteria decision approach (MCDA), where different criteria are assessed on their own scale, and flood risk is assessed through weighing the different criteria (Meyer *et al.*, 2009b). An additional challenge in FRA has been to address the analysis and communication of inherent variability and uncertainties in the FRAs (Apel *et al.*, 2006; Schanze, 2006; Zhou, 2012; Hall & Solomatine, 2008). These improvements in FRAs are important steps towards developing robust FRM approaches. Nonetheless, we identified some specific challenges and issues in FRA practices that still need to be addressed:

1. Temporal dimension of flood risk and adaptation.
2. Spatial dimension of flood risk and adaptation benefits.
3. New means to describe the occurrence of flood hazards.
4. Definition of flood risk - from one to several hazards.

These challenges are described below.

Challenge 1: Temporal dimension of flood risk and adaptation

Flood risk changes over time. As a result of climate change impacts we expect the occurrence and magnitude of flood generating hazards to increase, which in turn will increase flood risk (Arnbjerg-Nielsen, 2012; Zhou *et al.*, 2012). Methods are available for assessing changes in hazards based on for

example regional climate model (RCM) data (Grum *et al.*, 2006; Madsen *et al.*, 2009; Arnbjerg-Nielsen, 2011; Sunyer *et al.*, 2014), and these methods are utilized in FRAs to assess the temporal dimension of risk (Zhou *et al.*, 2012).

The overall temporal dimension in risk and positive effects of adaptation in FRAs introduce a rather complex system to be analysed with many variables that interact with each other. Describing and communicating these interactions correctly in the FRM process are important, and FRA methods should provide transparent and robust means to do so. The FRA method presented in this thesis provides a graphical description of the system at risk, which introduces a good alternative for describing the temporal dimension of risk transparently.

Challenge 2: Spatial dimension of flood risk and adaptation benefits

Flood risk can vary greatly in an area, and, yet, the spatial distribution of risk is rarely considered in regional FRAs (Meyer *et al.*, 2009b). A spatial FRA can be useful for several reasons. For example, a spatial risk profile provides information of sub-regions where risk exceeds the acceptable level, and where additional adaptation measures are needed. Further, a spatial risk profile allows for describing how the positive effect of adaptation measures are distributed over an area (Foudi, 2013) to assure that the chosen adaptation measure improve conditions in sub-areas where risk is high. This may become especially important in areas where several flood hazards may cause negative impacts, as adaptation measures may be more suitable for one hazard and less effective to tackle other hazards. Hence, spatial risk profiles increases our understanding on how risk varies and improves our possibilities to identify optimal adaptation (Foudi *et al.*, 2015). The FRA method presented in this thesis can be extended to include a spatial risk profile by dividing the studied area into sub-regions.

Challenge 3: Definition of flood risk – from one to several hazards

Total flood risk in an area is the sum of risks from all flood hazards, including consideration of their simultaneous occurrence. Presently, FRA most often focus on single hazard events (Pedersen *et al.*, 2012), i.e. flood risk is usually described using only one flood hazard, namely, the most threatening one. A FRA along a river catchment can be based on extreme discharges (Merz *et al.*, 2010) in the river; a low lying coastal region focuses the FRA on

extreme sea surges and dike breaks (van Manen & Brinkhuis, 2003); and urban regions with high imperviousness and extensive drainage systems may conduct FRAs based on pluvial flood hazards (Zhou *et al.*, 2012).

However, in many regions flood risk can be introduced by a multitude of hazards. For example, in an urban area located along a river, flood risk is a combination of pluvial and fluvial flooding. Focusing FRA solely on one hazard can potentially lead to large under- or over-estimations of the actual risk. This thesis presents a FRA method that can include multiple hazards to improve the accuracy of FRA and improve FRM practices.

Challenge 4: New means to describe the occurrence of flood hazards

Inclusion of multiple hazards into FRA may be challenging due to the need to describe the possible simultaneous occurrence of hazards. When concurrent events occur the hazards may interact, and total damage from such a concurrent event may be larger than for the hazards separately. To describe concurrent events accurately in FRA we need means to define how these events occur. However, often observations of concurrent events are unavailable or very few, and this complicates describing occurrence of concurrent events.

Large-scale atmospheric circulation influences local and regional climate (Kidson, 1994) and is considered an important factor when aiming at improving our understanding of local weather conditions and the occurrence of extreme events (Post *et al.,* 2002; Stehlik & Bárdossy 2002; Garavaglia *et al.,* 2010). This thesis explores the possibility to describe flood hazards by means of large-scale atmospheric circulation.

1.4 Objective

The objective of this thesis is to establish a transparent method for FRA by means of the Bayesian network approach. The method can in a flexible manner be extended to include multiple hazards in FRAs and describes the spatio-temporal risk profile and adaptation benefits. The focus in this thesis is on urban FRA.

1.4.1 Bayesian networks as means to address FRA challenges

Bayesian networks (BNs) have become an increasingly popular method for modelling uncertain and complex systems (Fenton & Niel, 2012; Uusitalo, 2007) and are considered a powerful tool for presenting knowledge and assessments, and for reasoning under uncertainty (Cheng I., 2002; Lee *et al.*,

2009; Uusitalo, 2007). BNs have found many applications in environmental management (Varis & Kuikka, 1999; Borsuk *et al*., 2004; Bromley *et al*., 2005; Uusitalo, 2007; Aguilera *et al*., 2011; Barton *et al*., 2012).

The applicability of BNs in risk assessments has been demonstrated in previous research; Lee *et al.* (2009) used a BN for project risk management of a large engineering project, Pollino *et al.* (2007) applied BNs to ecological risk assessments, and Carriger *et al.* (2011) developed a risk assessment and decision-making tool for pesticide risk management. The hypothesis of this thesis is that the BN approach is a suitable method for improving FRA to meet the challenges described above. The method is exemplified for an urban catchment, although the method could easily be transferred to other FRA issues as well.

1.4.2 Thesis outline

This thesis provides, firstly, an introduction to BNs and a description of benefits and limitations for using this approach in FRA (chapter 2). In chapter 3, the theoretical and methodological framework for the FRA method is presented. Chapter 4 expands the initial methodology to include more detailed descriptions of how other aspects of flood risk are handled, such as the spatial and temporal dimension. Chapter 6 presents the inclusion of several hazards into the FRA method based on a BN. Further, in chapter 5 the analysis for describing the relationship between large-scale atmospheric circulation and flood generating events is presented and discussed. Finally, in chapter 7 an overall case study to assess a spatio-temporal risk profile with multiple hazards for an urban catchment is presented.

In addition, this thesis includes 4 journal papers (Paper I, II, III, IV). Table 1 outlines how the journal papers are related to the 4 challenges presented in the introduction.

Table 1. Connection between the four journal papers and the four challenges that this thesis addresses

	Paper I	**Paper II**	**Paper III**	**Paper IV**
Challenge 1	X		X	X
Challenge 2				X
Challenge 3		(x)		X
Challenge 4		X		(x)

2 Bayesian network methodology in flood risk assessments

This chapter describes the Bayesian network (BN) approach in the context of applying it to FRA. An initial introduction to BNs and their extended for Influence Diagrams (IDs) is followed by a discussion of the advantages and limitations of using IDs in the context of FRA.

2.1 Introduction to Bayesian networks approach for flood risk assessments

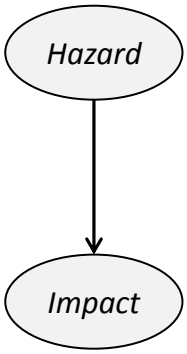
The core idea of BNs is to describe the causality between variables in a system through conditional probabilities (Charniak, 1991; Fenton & Neil, 2012). Causality is the relationship between an event (the *cause*) and another event (the *effect*). A Bayesian network (BN) is a probabilistic graphical model that consists of a set of variables, called *chance nodes* (elliptical shape), and a set of directed arrows (*links*) that describe the causal dependencies (Jensen & Nielsen , 2007).

There are two principle steps in developing a BN. Firstly, a graphical representation of the system's causal dependencies is developed (Borsuk *et al.*, 2004). In FRAs the aim is to describe the causal relationships between variables that contribute to flood risk in a system. The system refers to the context in which risk occurs, for example an urban catchment, river catchment, coastal area etc. Figure 2 (left) presents a simple BN with an *Impact* node, the effect, and a *Hazard* node, the cause. The Impact node may also be called a leaf node because it has no outgoing links, and it is a child node to the Hazard node. The Hazard node is a root node because it has no incoming links, and it is a parent node to the Impact node. These two nodes describe the core of BNs as used in FRA.

Secondly, input data into each node is defined. Root nodes are not conditional to any nodes and therefore an unconditional probability table needs to be defined, i.e. a single column table describing the prior probability density function (pdf). Child nodes are assigned *conditional probability tables* (CPTs). A CPT quantifies the probability of a node being in a particular state, given the states of the variables linking to it, i.e. the parent nodes (Borsuk *et al.*, 2004; Catenacci & Giupponi, 2010). In Figure 2, the Hazard node is as-

signed an unconditional pdf, and the Impact node is assigned a CPT that defines the probability of each possible impact given each possible hazard.

Once input data has been defined on all nodes in the BN, the network is compiled, i.e. the multivariate pdfs for each child node are calculated using the *Law of total probability*. Figure 2 (right) shows the equation for the multivariate probability of the *Impact*, *P(Impact)*. The Law of total probability requires that states described in the parent node (in this case the Hazard) are mutually exclusive, i.e. the hazard events in one node cannot occur simultaneously, and exhaustive, i.e. at least one of the events must occur. As such a BN can be used in "top down", or causal reasoning, which aims at specifying how causes generate effects (Barton *et al*., 2012). Hence, in FRAs BNs are used for describing how hazards generate impacts.



Law of total probability:

$$P(Impact) = P(Impact \mid Hazard)P(Hazard)$$

Bayes' theorem:

$$P(Hazard \mid Impact) = \frac{P(Impact \mid Hazard)P(Hazard)}{P(Impact)}$$

Figure 2. Left: a simple BN with two nodes, Hazard and Impact Right: Law of total probability and Bayes' theorem.

BNs are also often used for "bottom up", or diagnostic, reasoning (Barton *et al*., 2012). In these cases, evidence about the occurrence of the effect is used to characterise the causes. Diagnostic reasoning uses Bayes' Theorem as described in Figure 2 (right), which allows calculation of the probability of the each Hazard state given the observed Impact, *P(Hazard | Impact)*.

Bayesian inference is the process of updating probability distributions based on new information about the different variables in the systems, either through observation of node states or through decisions made (Charniak, 1991). For example, in FRAs the prior distributions of hazards may be updated when new information and measurements of the hazard becomes available. Hence, the initial FRA can easily be updated.

A basic BN can be extended to a Bayesian Influence diagram (ID) by including *decision* (symbolized with a rectangular shape) and *utility nodes* (symbolized with a diamond shape) (Carriger & Newman, 2011). Each decision node

represents the possible states of a decision that can be tested in the system. The decision node has no CPT, but instead possible states of a decision are listed in the node and the decision made is assigned a probability of one and all other states are zero. Utility nodes are cost functions that compute the expected utilities/costs from decisions (HUGIN, 2012).

2.1.1 Exploration of causality in an Influence diagram

The fundamental task in the development of an ID is the careful construction of the causal relationships between nodes. Figure 3 summarizes the different causal relationships that are used to construct an ID.

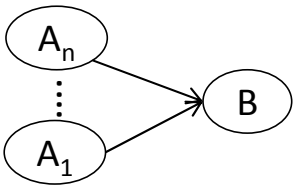
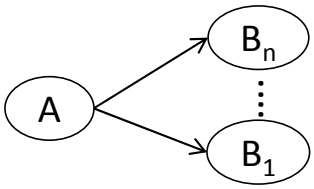
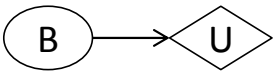
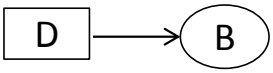
COMMON EFFECT CAUSALITY 	**Equation**: $$P(B) = P(B \mid A_1 \dots A_n)P(A_1) \dots P(A_n)$$
COMMON CAUSE CAUSALITY 	**Equation:** $$P(B_1 \dots B_n) = P(B_{1\dots n} \mid A)\, P(A)$$ Note: A and $B_1 \dots B_n$ are calculated as direct causality. The dependency between the effects ($B_1 \dots B_n$) is described in a mutual child node
UTILITY CALCULATION 	**Equation:** $$U = \sum_{k=0}^{m} B_k P(B_k)$$ where m is the number of intervals in B and k = 0…m
DECISION 	**Equation:** $$P(B) = P(B \mid D)\underbrace{P(D)}_{=1}$$ Note: P(D) = 1 because the user of the network makes a decision.

Figure 3. Description of causality in an ID. Further, the utility and decision assessment in the ID is described.

Causality in the network is described as *common effect* or *common cause* causality. Common effect causality defines the multivariate probability distribution for node B (the effect), *P(B)*, based on multiple causes (A_1 ... A_n). In common cause causality one cause (A) is linked to several effects (B_1 ... B_n). The relationship between the effects is indirectly described through a common child node as common effect causality. The utility calculation defines the expected utility (U) from node B and is the sum of all states *k* in B (B_k) multiplied with the probability of state *k*, $P(B_k)$. A decision node is linked to

the variables that it affects directly. The decision node lists the different states of a decision, including a "no action" option, which is the initial stage of the node. When the decision node is updated, i.e. a specific decision is taken; the decision is allocated the probability 1. The child node (B) is updated according to the pre-defined CPT in that child node.

2.2 Advantages and limitations for using an Influence diagram in flood risk assessments

This chapter reviews some of the main advantages and limitations of using IDs in FRA.

2.2.1 Combining multiple data sources with IDs

Interdisciplinarity refers to the integration of two or more disciplines focused on a common and complex problem (Holbrook, 2013). FRM is an interdisciplinary process (Levy, 2005) as it integrates traditional engineering, economics, social sciences, decision theory etc. Hence, a wide range of data and assessments from different sources need to be combined for integrated decision support. This creates a complex decision-making problem. To model such complexity, interdisciplinary and holistic approaches are needed (Varis *et al.*, 2012).

One important feature of IDs is that they can easily and in a mathematically coherent manner incorporate information and knowledge from different sources (Uusitalo, 2007). A FRA requires information of hazard measurements, flood simulations, various future scenarios, economic data analyses and parameters, spatial impact assessments etc., and this can be combined in IDs. Hence, IDs do not replace existing models; rather they use the output from various models converted into a suitable format to be used in IDs (Bromley *et al.*, 2005).

If no data is available for some variable, expert opinions/knowledge can also be used in a coherent and transparent manner in an ID (Farmani *et al.*, 2012; Henriksen *et al.*, 2012; Varis *et al.*, 2012). Hence, IDs may combine subjective and objective information flexibly (Bromley *et al.*, 2005). Expert assessment is an established approach to obtaining estimates of relationships, variances around model parameters, model-predicted values etc. (Uusitalo *et al.*, 2015). Inclusion of expert judgments can easily be criticized as too subjective, but is a valid alternative where data availability is limited (Uusitalo *et al.*, 2015).

Further, the method can incorporate data with different accuracies (Uusitalo, 2007). The input data to IDs can be formulated as detailed pdfs, or as point estimations where this is the only available information about the variable. However, the output from an ID is only as good as the input data, and, therefore, it is important to consider the suitability of data sources when modelling decision-problems in IDs. Depending on the decision problem, level of detail of the data input may crucially affect the robustness of the analysis.

2.2.2 Uncertainty in IDs

Uncertainty in FRAs stems from a range of sources and poses challenges on how the results of an FRA can be used to identify optimal adaptation options. A wide range of uncertainty classification can be found in literature (Skinner *et al*., 2014; Henriksen *et al*., 2012; Refsgaard, 2012; Uusitalo *et al*., 2015; Refsgaard *et al*., 2007; Regan *et al*., 2002).

Commonly uncertainty is divided into two categories (Uusitalo *et al*., 2015; Catenacci & Giupponi, 2010): aleatory and epistemic uncertainty. *Aleatory* uncertainty describes inherent randomness and natural variability and is often called irreducible uncertainty. In FRA aleatory uncertainty arises from, for example, natural variability of flood hazard occurrence as hazard patterns are not identical from year to year (Compton *et al*., 2009). However, statistical distributions that describe the probability of extreme events can be developed based on data analysis of historical measurement to describe aleatory uncertainty. *Epistemic* uncertainty is a result of imperfect knowledge of the system. In FRA, epistemic uncertainty can arise from, for example, measurement errors of hazard (Compton *et al*., 2009) or errors in the impact assessment. If available, a combination of several data sources in the analysis may be a way to describe the epistemic uncertainty in FRA.

Many types of uncertainty are present in decision analysis, and it is not always possible to separate the various types (Uusitalo *et al.*, 2015). In management practices it is often a challenge to describe uncertainties in a manner that they can objectively support decision making (Barton *et al*., 2012). This is also the situation in FRM. In many sectors of environmental management, for instance integrated water resources management and ecological management, the Bayesian network approach has become an increasingly popular method in aiding decision-making to modelling of complex systems under high uncertainty (Varis, et al., 2012).

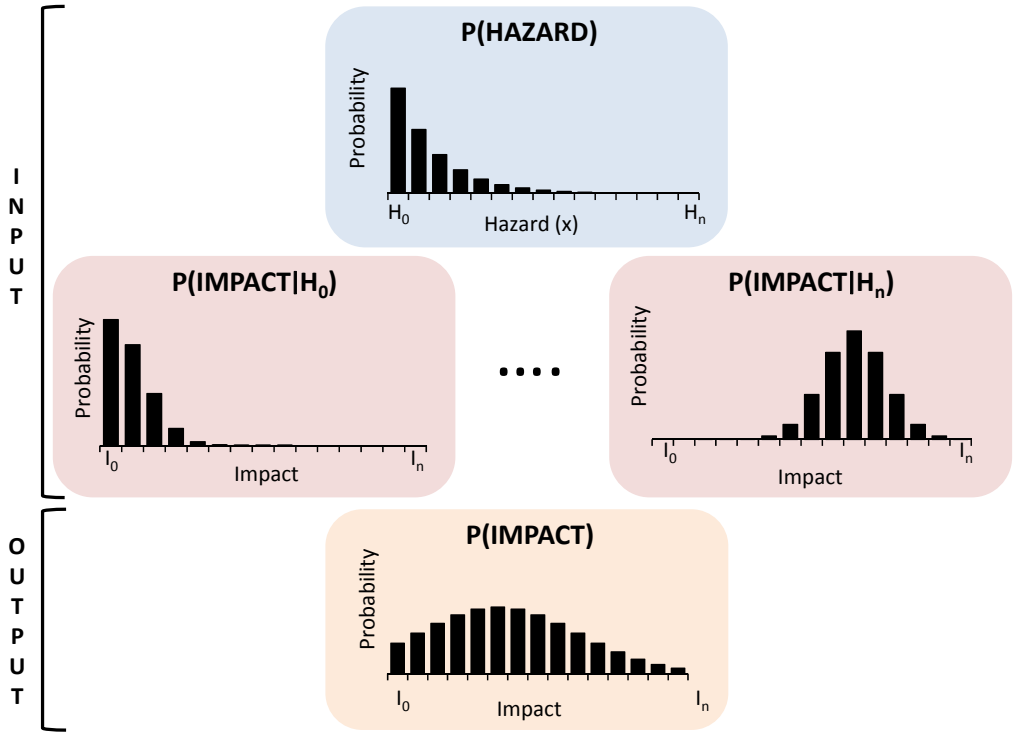


Figure 4. Illustration of how uncertainty is described in an ID (Based on the simple BN in Figure 2). P(Hazard) describes how likely different magnitudes of a hazard (H_0 ... H_n) are to occur. Impacts are assessed for each magnitude of the hazard, i.e. $P(Impact \mid H_0)$ to $P(Impact \mid H_n)$ and are described as pdfs to account for uncertainty of the impacts. The compiled ID describes the overall uncertainty of the impacts in the ID, *P(Impact)*.

IDs use pdfs as a measure for uncertainty of variables whose state are not certain (Farmani *et al*., 2012) by indicating how likely an outcome is (Uusitalo *et al*., 2015). The wider the probability distribution, the higher is the uncertainty. Figure 4 illustrates how uncertainty is described in an ID using the simple BN from Figure 2 as an example. *P(Hazard)* describes how likely different intervals of a hazard (H_0... H_n) are. i.e. the pdf describes aleatory uncertainty. Epistemic uncertainty, for example, measurement errors, can be included in the ID by developing several pdfs from various hazard sources.

Impacts are assessed conditional to each hazard interval that causes the impact, i.e. $P(Impact \mid H_0)$ to $P(Impact \mid H_n)$. In impact assessments, the common approach is to use stage-damage curves to assess point estimates of damage for different water depths. Uncertainty bounds are rarely included to these curves, although, considerable uncertainties, both aleatory and epistemic, are present. To include pdfs to the impact nodes uncertainty assessment of the utilized stage-damage curve is needed. The compiled ID describes the overall uncertainty of the impacts in the ID, *P(Impact)*. Hence, uncertainty for each node is described as a combination of uncertainties of all variables

that are prior to that node and the uncertainty of the node itself. IDs apply the Bayesian view of probabilities. The Bayesian interpretation considers probability as a degree of belief that the event will occur, given the relevant information available (Catenacci & Giupponi, 2010). Hence, probability is a function of the state of available information.

Due to the probabilistic representation of interactions between variables, IDs are better at representing risk and uncertainties than models, which only account for deterministic values (Uusitalo, 2007). With regard to decision analysis, which is the aim of FRAs, several studies have concluded that uncertainties need to be handled explicitly in order to select optimal adaptation and policies (Henriksen *et al*., 2012; Catenacci & Giupponi, 2010; Uusitalo, 2007; Barton *et al*., 2012). Uncertainties described in chance nodes are by all means explicit (Bromley *et al*., 2005), and for representation of uncertainty, IDs are a powerful and rational method for decision support (Henriksen *et al*., 2012).

2.2.3 Risk communication with IDs

The challenge in communicating flood risks and their related uncertainties has become an increasingly important aspect in scientific research (Morss *et al*., 2005; Faulkner *et al*., 2007; Pidgeon & Fischhoff, 2001). In FRA, flood risk and uncertainty need to be communicated to practitioners involved in the decision-making process to ensure the development of efficient adaptation plans. Faulkner *et al.* (2007) point out that scientists often communicate uncertainties through mathematical formulations using scientific definitions. This may not be the most efficient way to describe scientific uncertainties and their implications to practitioners, who do not necessarily have the appropriate background to understand the scientific language. Instead, studies have shown that practitioners are in need of tools that in a visual and clear manner are able to provide a description of the information important for decision-making and for understanding the implications of the underlying uncertainties (McCarthy *et al*., 2007; Faulkner *et al*., 2007).

The graphical description in an ID provides precisely the sort of visual description that is needed to explain the overall risk and uncertainties in a system (Bromley *et al*., 2005; Catenacci & Giupponi, 2010; Uusitalo, 2007; Barton *et al*., 2012). In FRA, the visualization of the system at risk makes the assessment more transparent and, therefore, encourages communication and ensures that the problem formulation is understood and agreed upon. Henriksen *et al.* (2011) argue that the novelty of the Bayesian network methodology

is not that is serves as a technical tool but rather that it allows for structuring challenging issues. IDs, notably, have the ability to represent scientific and technical complexity in a meaningful way and translate technical and expert language into easily understood graphical models (Henriksen *et al*., 2012).

2.2.4 Limitations and challenges for using IDs in FRAs

Whereas several advantages for the use of IDs in decision analyses and risk assessments have been identified in resent research as discussed above, there are also limitations and challenges in the use of the methodology.

One major challenge is the need for discretisation of distributions of continuous variables (Uusitalo, 2007). Environmental variables and parameters often have continuous values, but the BN methodology, or especially the available software's developed to construct BNs, are very limited in its abilities to deal with such variables. Hence, these values are often discretised, which can lead to loss of information. A common way to transform continuous values into discrete values is by to divide the continuous distribution into intervals (HUGIN, 2012).

With regards to presenting detailed uncertainties in an ID, the inclusion of probability distributions at each node requires large amount of data, information and analyses (Catenacci & Giupponi, 2010), and financial costs of the analysis itself may become significant. While IDs are well suited for describing complex interactions between a range of variables, it may still be beneficial to reduce the complexity of the analysis by only including the most important variables and relationships for the specific assessment.

Varis *et al.* (2012) argued that one challenge in introducing IDs to a wider range of experts is that the majority of experts are not familiar with the theoretical background of the Bayesian methodology. Furthermore, the Bayes principal and the way subjectivity and uncertainty are incorporated into the IDs constitute barriers between Bayesian and non-Bayesian modellers.

Several studies have also concluded that a major weakness of the BN approach is that it is unable to describe feedback loops, i.e. it does not allow for returning to a node and thereby accounting for cyclic dependencies. (Henriksen *et al*., 2012; Catenacci & Giupponi, 2010; Uusitalo *et al*., 2015; Bromley *et al*., 2005). In FRAs and climate change impact assessments this may be overcome by using dynamic BNs (Catenacci & Giupponi, 2010). This is discussed further in chapter 4.2.

3 Flood risk assessment framework

In the chapter, firstly, the methodological framework for FRA as applied in this research, is described. Secondly, the integration of a Cost-benefit analysis (CBA) into the method is presented.

3.1 The methodological framework – An Influence diagram (ID) for flood risk assessment

The methodological framework for the FRA presented in this thesis is illustrated as an ID in Figure 5. The links between the nodes describe the causal relationships that are accounted for in the methodology. The framework is divided into 1) hazard analysis, 2) impact and adaptation assessment, 3) risk assessment, and is integrated with an economic assessment as described in 3.2.

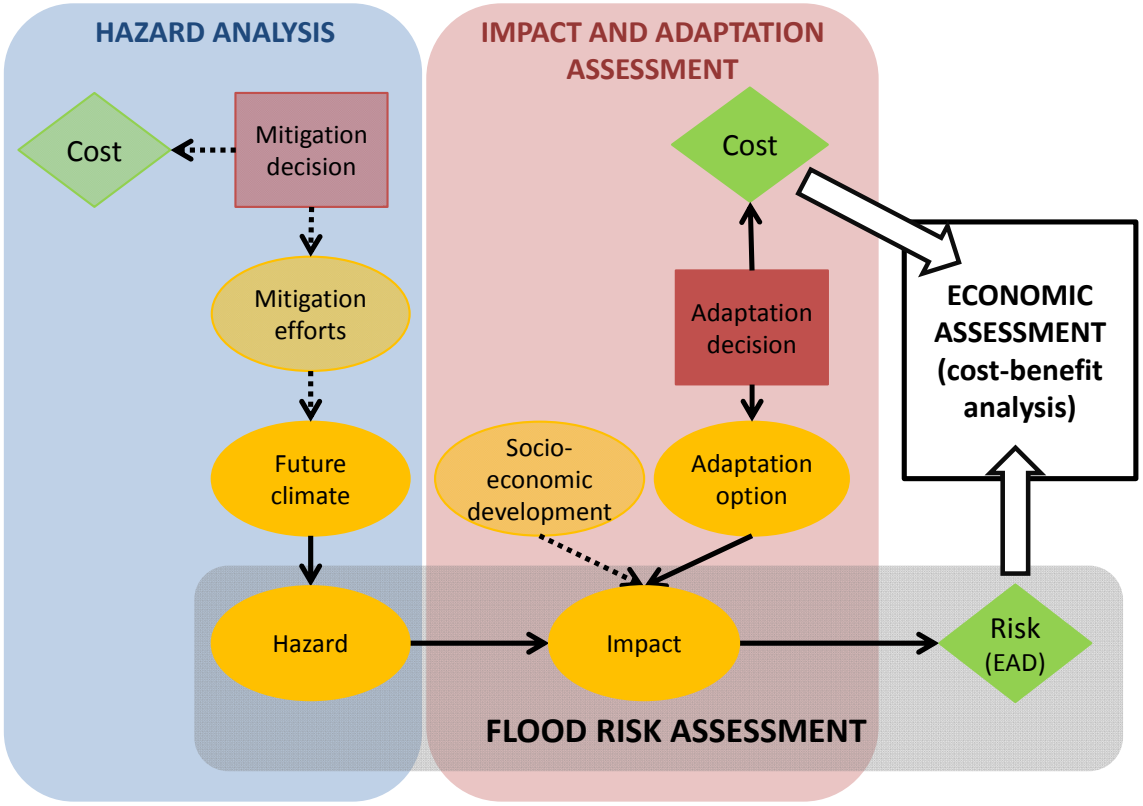


Figure 5. Methodological framework for FRA using an ID. The nodes describe the different variables in the system and the links describe the causal dependencies. The framework is divided into 1) hazard assessment, 2) impact and adaptation assessment, 3) risk assessment, and is integrated with a Cost-Benefit analysis (CBA).

3.1.1 Hazard analysis

The objective of the *hazard analysis* is to describe the magnitude and occurrence probability of the hazards that introduce risk to the system. The unit of the hazard node depends on the overall aim of the FRA. In paper I the pdf for the hazard node describes the annual probability of water depths at one specific point along a railway track to assess the railway company's risk. In paper III the hazard node describes the daily hazard occurrence probability. Paper IV includes two hazard nodes, one describing daily precipitation and one describing daily maximum sea water levels. The inclusion of multiple hazards is described in detail in chapter 5.

Climate change is expected to affect the occurrence and magnitude of flood hazards (Arnbjerg-Nielsen, 2012; Grum *et al.*, 2006; Madsen *et al.*, 2009). The *Future climate* node describes these anticipated climate change impacts on the hazard. If risk is assessed in the present, then the future climate node is not needed, and the hazard pdf can directly be assessed from observed hazard events.

Figure 6 presents the hazard data analysis conducted in paper III and IV for the development of input data to the hazard node. To develop the hazard pdf in present time, extreme event observations are used. The hazard extremes are fitted to a suitable parametric pdf; in papers III and IV the extreme events were assumed to fit an exponential distribution. To describe the probability of extreme events in a future time period, regional climate model (RCM) data for control and future period are analyzed, and a change between these time periods is assumed to describe the future changes as climate factors. These climate factors are applied to the pdf parameters that represent the present hazard situation. Lastly, the continuous pdfs need to be discretized before they can be used in an ID.

Climate change impacts can be reduced through climate change mitigation, which, in the framework, is described using a *Mitigation effort* node. Mitigation is defined as anthropogenic interventions with the aim of reducing greenhouse gases in the atmosphere (IPCC, 2007b). The mitigation effort node can be used to analyse the positive effects of proposed mitigation policies.

When mitigation policies are tested in the *Mitigation decision* node, the hazard node is updated accordingly. Similarly, both the *cost* node and the total expected cost of the tested mitigation effort are updated. However, on a very local or regional level, where risk assessments are commonly conducted, es-

timation of how mitigation efforts may affect hazard occurrence is challenging. Hence, for the application of this framework for local FRA (as presented in papers I, III and IV) it is assumed that any mitigation efforts are accounted for in the climate change impacts (i.e. in the data used in the future climate node), and, therefore, no specific mitigation efforts are included in these applications of the framework.

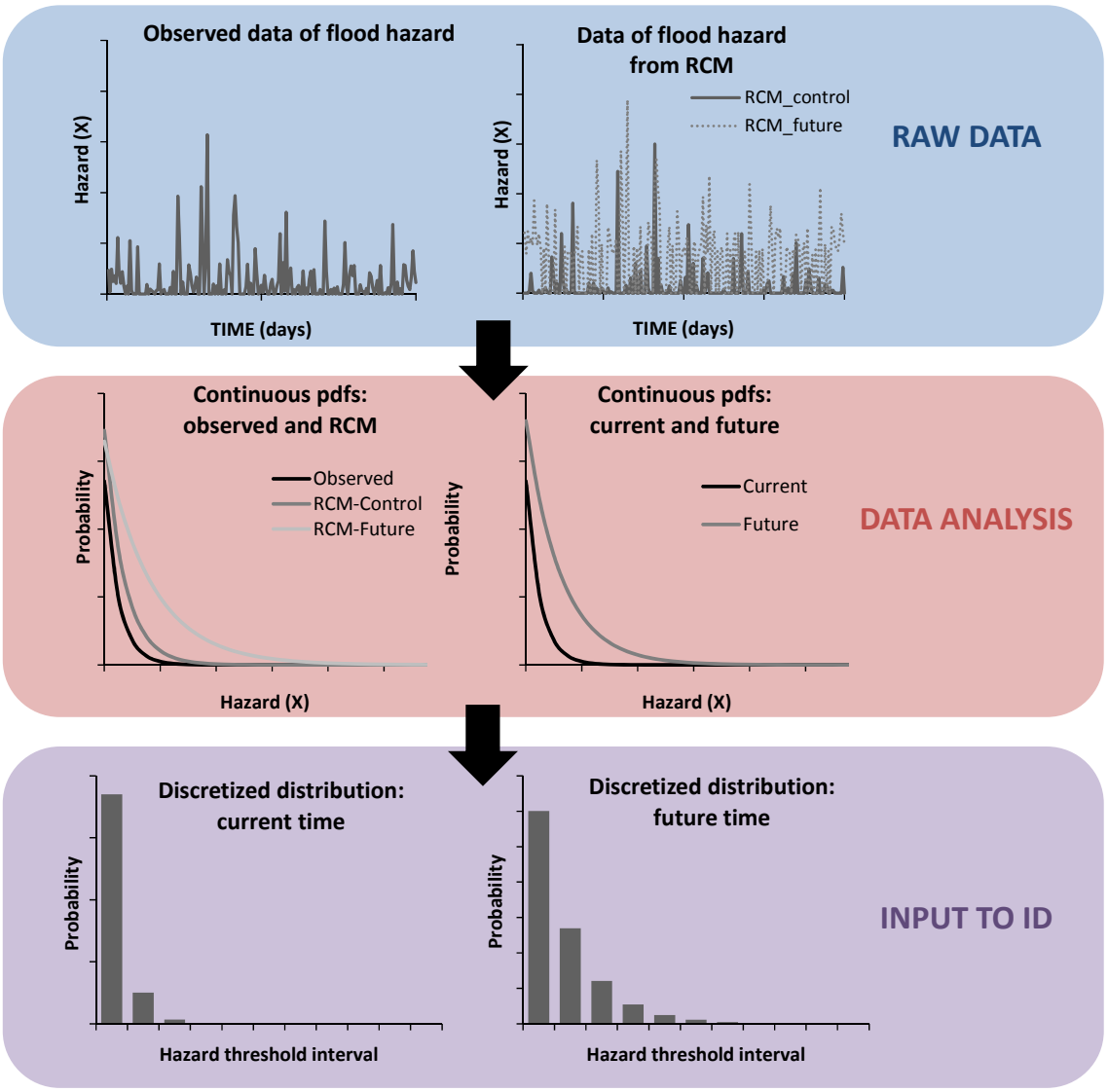


Figure 6. Hazard node input data preparation. Raw observed data and data from RCMs are used to estimate continuous pdfs in observed and future time periods. The continuous pdfs for current and future time are discretized before use in an ID.

3.1.2 Impact and adaptation assessment

An *impact assessment* describes the severity and spatial extent of the expected negative impacts (consequences) of a hazard. Impacts are a direct result of vulnerability in the system being studied. Vulnerability is a term dis-

cussed extensively in literature, and has been given many definitions (Yohe & Tol, 2002; Adger, 2006; Hinkel, 2011). The general consensus is that vulnerability is a measure of possible future harm (Hinkel, 2011) to the geophysical, biological and socio-economic systems (IPCC, 2007a). Hence, vulnerability depends on the nature of the system being analysed (Brooks *et al.*, 2005).

The Third Assessment Report (TAR) of the IPCC (McCarty *et al.*, 2001) defines vulnerability as a function of exposure, sensitivity and adaptive capacity. Exposure is the degree to which a system is exposed, i.e. the presence of economic, societal, and environmental assets that can be affected (IRGC, 2005). Sensitivity refers to how dependent the system is on the assets that are exposed. Adaptive capacity is generally described as the ability of a system to adjust to risk by for example moderating potential damage, taking advantage of opportunities or coping with the negative consequences from floods (McCarty *et al.*, 2001; Brooks, 2003).

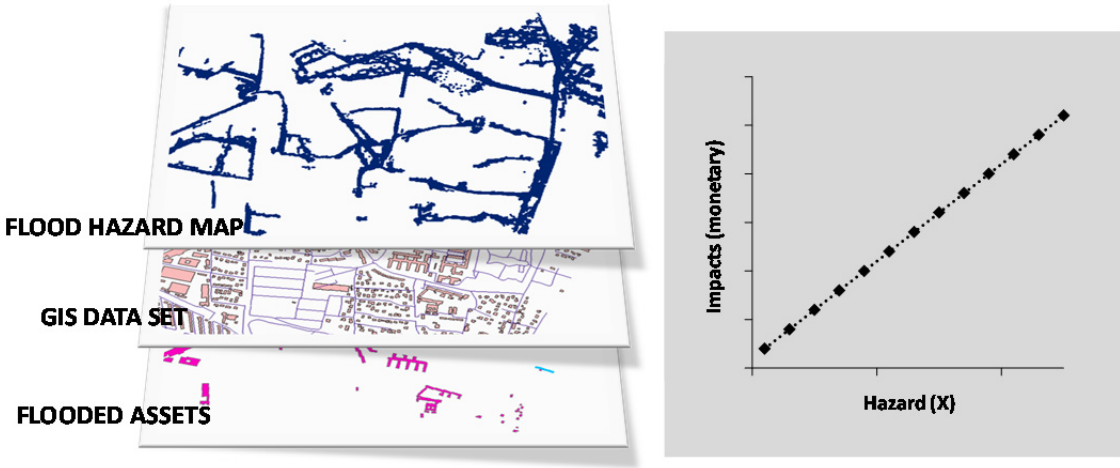


Figure 7. The workflow for the impact assessment. Impacts are assessed through a combination of information from a flood hazard map and GIS data. This results in detailed information on flooded assets in the study area.

The impact node describes the expected adverse effects for the flood hazard occurrence in a CPT. The workflow of the impact assessment, as conducted in this thesis, is presented in Figure 7. The assessment is conducted though simulations with a coupled 1D-2D model (MIKE URBAN). The 1D sewer model is used to simulate the underground pipe flow and the 2D inundation model is used to assess the water depth and extent of the overland flow. The output from the 1D-2D model, i.e. a flood inundation map, is combined with spatial data of the system in a Geographic Information System (GIS)-based model. For example in an urban environment spatial data for different dam-

age categories (houses, roads, stores, population etc.) are combined with the inundation map. The total impacts are calculated for each hazard threshold by assessing number of assets in each damage category using critical thresholds to define flooded assets and combining that with unit costs (Zhou, 2012). This is described in more detail in paper IV.

In this framework, the *Impact node* is causally dependent on the hazard node, the *adaptation option node* and the *socio-economic development* node. Adaptation involves all initiatives and measures that aim at reducing harm on the natural and human system by reducing vulnerability (Hauger *et al*., 2006). When an impact assessment is conducted, the positive effects of various adaptation options are also assessed.

Adapting urban areas to climate change involves decisions across a landscape of individuals, companies, civil society, public bodies, governments at different levels, and international agencies (Adger *et al*., 2005). This framework does not include the complex network of practitioners in which actual decisions are made in, or the identification of possible adaptation options, but views adaptation from the point where feasible adaptation options are identified.

The adaptation option node is a descriptive node that includes all possible versions of an adaptation measure (as states that the node may take) that are considered, including a "no adaptation" option, which is the initial state of the node. The adaptation option is tested by the user of the network through the *adaptation decision* node, which is linked to the impact node as it directly changes the expected damage from flooding. Hence, if adaptation measures are included in the network, the impact node includes pdfs describing impacts both with and without adaptation. If an adaptation measure is chosen in this node, the corresponding cost of the adaptation is updated in the utility (*cost*) node, and the impacts are updated according to the pre-defined pdfs in the impact node's CPT. Impacts and adaptation are discussed more in detail in chapter 4.1.

Finally, *socio-economic development* refers in this framework to regional development such as population growth or increase in valuable assets within the system, i.e. it is a description of change in valuable assets that may lead to change in impacts and, hence, risk. In the methodological framework socio-economic development may be included in an FRA as a separate node that is directly linked to the impact node. The use of a socio-economic scenario in FRA is exemplified in paper III.

3.1.3 Risk assessment

The *risk assessment* combines the outputs from the impact assessments and the hazard analyses to describe flood risk. In engineering approaches, flood risk is commonly defined as Expected Annual Damage (EAD) (Helm, 1996; Hauger *et al.*, 2006; Zhou, 2012; Olsen *et al.*, 2015). In papers I, III, and IV this definition of risk is applied. However, if a MCDA is preferred for decision-support, the risk unit(s) can vary. This is discussed in paper III.

Risk is assessed when the ID is compiled, i.e. multivariate pdfs are assessed for each variable in the system and the EAD is defined by means of the pdf for the Impact node. In paper I impacts are described as an annual pdfs and EAD (expected utility) is calculated as presented in Figure 3. In paper III and IV the hazard node is described though daily probability distributions. Therefore, the impact is described as daily damage costs and the EAD in the network is calculated as:

$$EAD = 365\ EDD = 365 \sum_{k=0}^{n} Impact_k\, P(Impact_k) \qquad (1)$$

where EDD is the *Expected Daily Damage*, $Impact_k$ describes each possible impact interval (in monetary terms), and $P(Impact_k)$ is the probability of $Impact_k$.

Hence, the presented FRA method is utilized for calculating EAD and for testing how EAD changes when different adaptation measures and combinations of adaptation measures are implemented.

3.2 Economic assessment of adaptation options

To define optimal adaptation, the ID is integrated with a cost-benefit analysis (CBA) in papers I, III and IV. The general purpose of the CBA is to compare the benefits of a project with its corresponding costs of implementation, and this provides valuable insight to decision-makers on how to prioritize adaptation options (Pearce *et al.*, 2006).

This socio-economic framework is presented in detail by Zhou *et al.* (2012). In the socio-economic framework, benefits from adaptation are assessed as the difference in EAD before (no adaptation) and after implementation (adaptation yr t_0 or t_n) of adaptation options, as presented in Figure 8. Benefits are calculated from the year after the implementation. Costs are the implementa-

tion costs. Total added cost form climate change is the total difference between EAD without adaptation (red line) and EAD assuming no climate change (black line).

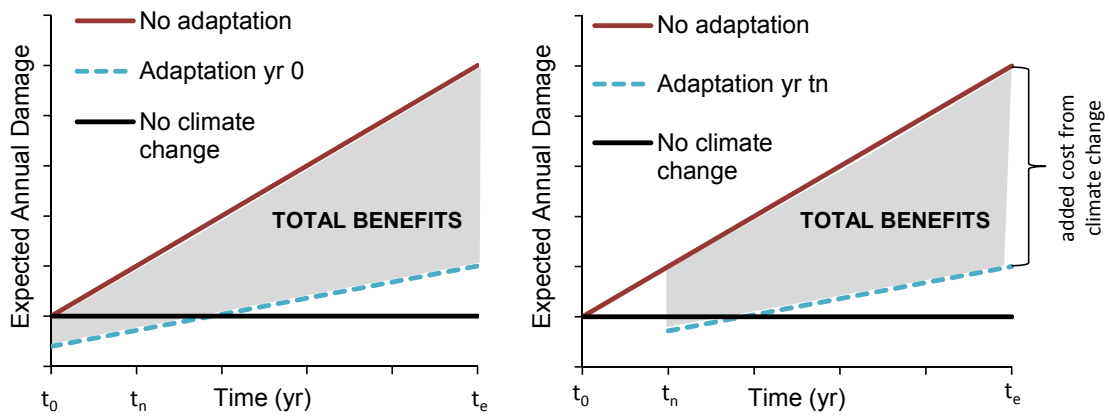


Figure 8. Illustration of socio-economic framework for adaptation assessment. Left: Adaptation implemented at year 0. Right: Adaptation implemented at year t_n. Total benefits of adaptation are the saved costs from climate change impacts. The socio-economic framework is adapted from Zhou *et al.* (2012).

Net present value (NPV) describes the net benefits of a project and is used as decision rule for comparing the costs and benefits of adaptation using discount rate r over time period t calculated as:

$$NPV = PV_B - PV_C \tag{2}$$

$$PV_B = \sum_{t=t_0}^{t_e} \frac{B_t}{(1+r)^t} \tag{3}$$

$$PV_C = \sum_{t=t_0}^{t_e} \frac{C_t}{(1+r)^t} \tag{4}$$

where PV_B is the discounted benefits, and PV_C is similarly the discounted costs, B_t is the benefit in year t, C_t is the cost of adaptation in year t, and t_e is the life time of the adaptation measure. A positive NPV indicates an economically attractive project. Discounting is applied to express benefits and costs in their present values. A discount rate of 3 % is recommended by the Danish Environmental Protection Agency (Damgaard *et al.*, 2006) and is, hence, applied in papers I, III and IV.

The best timing for adaptation implementation is the year, t_n, when the net benefits are the highest in the end of the assessment period t_e. This is exem-

plified in Figure 9. Adaptation is implemented in t_0 and t_n assuming that benefits from adaptation implementation remain similar at any point in time. Figure 9 illustrates three cases where the cost of adaptation is low, medium and high, and exemplifies how this affects the timing of adaptation implementation. With low implementation cost, best time for implementation is in t_0, with medium cost net benefits are similar in time t_0 and t_n, and with high implementation costs t_n is the best time for implementation. This reflects that with certain adaptation benefits, the cost of the adaptation has to be suitable for implementation currently. Otherwise, implementation of adaptation should be postponed until the benefits of the adaptation increases as a result of climate change effects.

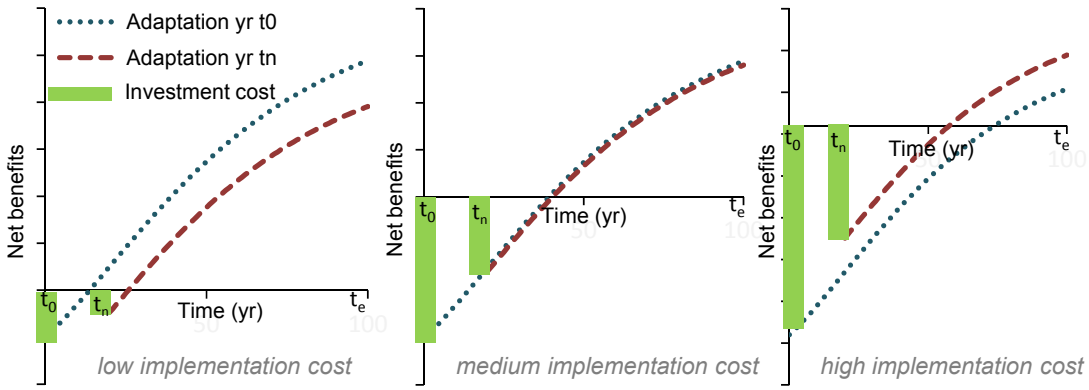


Figure 9. Cumulative net benefits of adaptation implementation. Adaptation implemented in year t_0 and t_n. It may not immediately be beneficial to implement adaptation measures with high implementation costs due to relatively low initial climate change impacts. Therefore, the best timing for adaptation implementation is assessed using the NPV.

4 Expansion of the methodology: meeting detailed needs of flood risk assessments

The chapter expands the ID method presented in the previous chapter to address selected specific challenges of FRA. Firstly, the ID is extended to include multiple impacts and adaptation options. Inclusion of multiple adaptation options is exemplified in papers III and IV. Multiple impacts are used in papers I, III and IV. Secondly, the inclusion of a temporal dimension of flood risk is illustrated. This is further described in papers I, III and IV. Thirdly, the ID method is expanded to include the spatial dimension of flood risk. This is shown in paper IV.

4.1 Multiple impacts and adaptation options

In FRM, various adaptation measures and initiatives are implemented to reduce different adverse impacts associated with flooding (Parry *et al*., 2007; Smit *et al*., 2000; Poussin *et al*., 2012). Adaptation options can be classified in several ways to clarify the use of the adaptation and to aid in choosing the right adaptation options for different FRM challenges. For example, Refsgaard *et al*. (2012) classified adaptation according to *the intent, timing, spatial* and *temporal* scope of the adaptation option.

The *intent* of adaptation refers to whether the adaptation measure is planned or spontaneous. Spontaneous adaptation measures tend to be taken by individuals, and planned measures are generally implemented through a decision-making process by governmental/local practitioners. In the FRM approach presented in this thesis, which focus on the decision-making process at a local/regional level, mainly planned adaptation options are considered.

Timing of adaptation measures refers to reactive versus anticipatory forms of adaptation (Smit *et al*., 1999; Refsgaard *et al*., 2007). Anticipatory adaptation, i.e. adaptation that takes place before impacts of climate changes are widely observed (IPCC, 2007c), can further be divided into structural and non-structural measures. *Structural* measures are constructed permanent facilities that reduce damage of flooding (Poussin *et al*., 2012), such as dikes and retention basins. *Non-structural* measures are means to educate and train the public or practitioners to change the perception on flood risk (Andjelkovic, 2001) and to change the behavior of for example individuals to

reduce negative impacts. This involves, flood preparedness, emergency response, and flood recovery.

The papers in this thesis focus on demonstrating the positive effects of planned and structural adaptation measures. Urban drainage improvements are assessed in papers I, III and IV. Benefits from construction of a flood wall along a sea coast are assessed in paper IV. In paper III, the benefits from construction of a retention basin are exemplified. Nonetheless, the FRA method presented in this thesis is not restricted to structural measures. Non-structural measures could equally be included into the FRA, if the expected positive effects of such measures could be described.

The *temporal* and *spatial* scope of adaptation options can be assessed directly in the ID by extending the FRA method presented in chapter 3. This is described further later in this chapter (chapter 4.24.2, temporal risk, and chapter 4.3, spatial risk).

Impacts are, generally, divided into *tangible* and *intangible* damages (Floodsite, 2009). Tangible impacts can be evaluated directly in monetary terms, while intangible impacts cannot, at least not directly, be assessed in such terms, for example, loss of life or health effects (Floodsite, 2009). Tangible impacts are further divided into *direct* and *indirect* losses (Thieken *et al*., 2008). Direct impacts are damage to assets as a result of direct contact to flood water, i.e. buildings, roads etc. Indirect impacts are damage from disruptions due to flooding, such as traffic delays and loss of business profit. Paper I describes impacts as direct tangible (cost from direct breakdown of infrastructure) and indirect tangible (cost from traffic delays). Paper IV mainly assesses risk by means of direct tangible costs (damage on buildings, roads etc.), but also an intangible impact (health) is included, although it is translated into monetary damage.

Often FRAs include primarily tangible impacts, and some argue that such FRAs are incomplete, as they neglect important intangible effects of flooding (Meyer *et al*., 2009b). Although approaches exist for including intangible effects into economic risk assessments, for example, through variables that have a monetary value (Lekuthai & Vongvisessomjai, 2001), these methods are often criticized for their complexity (Meyer *et al*., 2009b) and for ethical and moral reasons (Hansjürgens, 2004). For example, one often occurring moral discussion in flood damage assessments is how to put a price on loss of life.

Another approach for including intangible effects into flood risk assessments is through a multi-criteria decision analysis (MCDA). MCDA refers to making decisions using multiple criteria to describe risk. In an MCDA, different risk criteria are measured, each in its own scale, and total risk is assessed by applying specific weights to the different criteria. This allows decision makes to put more weight on the effects that are the most important to minimize (Meyer *et al*., 2009a). In paper III damage is mainly assessed from direct tangible losses, but the inclusion of intangible losses (affected people and damage on cultural heritage) in an MCDA is also exemplified and discussed.

In FRA, an ID is used to model the specific interactions between different adaptation options and impact categories. This is exemplified in Figure 10. Here, impacts are described as three nodes defined as the general damage categories: social, environmental and end economic. Each impact node is connected to a utility node to describe the expected risk. Economic damage is defined as EAD and can be directly integrated with a CBA. Risk from social or environmental damage, however, can be described with other risk units, when an MCDA approach if preferred.

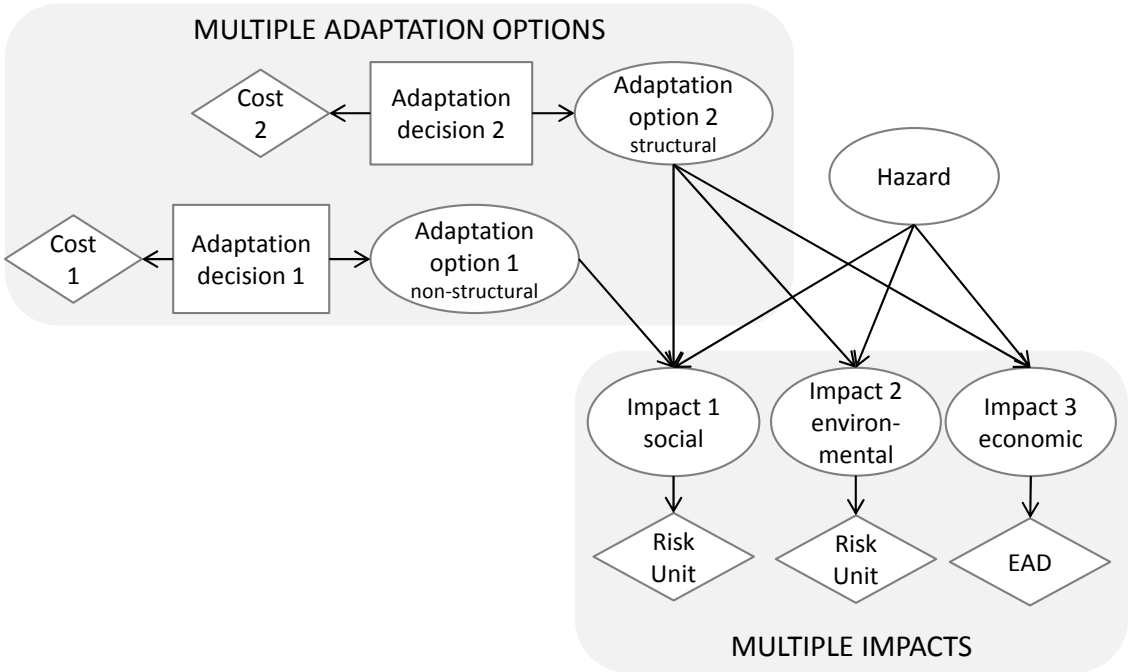


Figure 10. Multiple impacts and adaptation in flood risk assessments using an ID. Impacts can be described though social, environmental, and economic costs and the risk unit can be changes to other than EAD if a MCDA is preferred as a FRA method. Adaptation measures may be structural or non-structural, and they may interact with different impact categories.

Optimal flood adaptation is not obtained by one single adaptation measure; rather, a flood adaptation plan includes a combination of several measures. In Figure 10 adaptation is described as two adaptation nodes (one structural and one non-structural). The structural adaptation is connected with all impact categories. For example, an improved drainage system reduces the overall flooding in the system and, hence, decreases all impacts. The non-structural adaptation option is only connected with social costs. This could be the case, if an awareness campaign (non-structural adaptation) reduces the health impacts of flooding (social cost) as people become more aware of the negative impacts related to flood water.

Consequently, adaptation options of different characteristics can influence different impact categories, and an ID allows a systematic and explicit description of these interactions. This is one of the major strengths of using an ID in FRA. Obtaining the data needed to assess the influence of the different adaptation options may, however, require wide data analysis and assessments within very different disciplines. Further, in some cases, as for example evaluating the reduction in loss of life as a result of an awareness camping, obtaining data for the ID can be very difficult. In such cases expert opinions is a valid option.

4.2 Temporal dimension of risk and adaptation effects

The temporal dimension of flood risk and adaptation refers to change in risk and adaptation benefits over time as a result of climate change and regional socio-economic development. Although, a conventional ID is static, meaning that it models the system at one specific point in time, the network can be further developed into a dynamic ID to allow for a temporal FRA. Such an ID is exemplified in Figure 11.

A dynamic ID is developed by including so called *time slices* into the network (HUGIN, 2012; Catenacci & Giupponi, 2010; Uusitalo, 2007). Each time slice represents one specific year in the future. In the network presented in Figure 11, three time slices are included into the ID: a present and two future time periods. The ID can include as many time slices as desired, although careful consideration of the number for time slices is needed. Each time slice increases the complexity of the ID considerably and requires further data collection and analysis. An appropriate number of time slices is

such that risk and adaptation benefits are described with enough details for the specific FRA purpose.

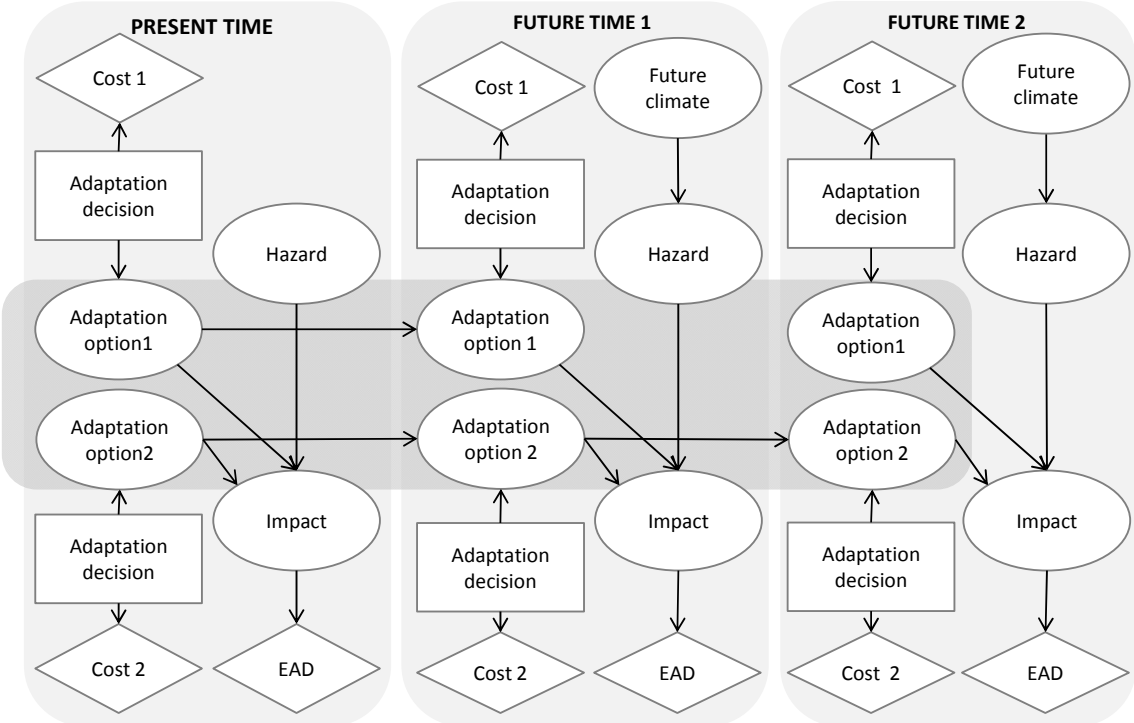


Figure 11. A dynamic ID for assessing the temporal dimension of risk. The ID includes two additional future time slices and describes risk in current and future time periods.

In the current time slice, the hazards variable is not affected by climate impacts. Hence, the future climate nodes are only linked with future hazard nodes. The time slices in a dynamic network are connected by linking the adaptation option nodes in the time slices with each other. Consequently, when adaptation options are chosen in one time slice, risk in all future time slices is also re-assessed.

The temporal scope of adaptation as defined by Refsgaard et al. (2012) refers the fact that adaptation options may have varying temporal effects on the impacts. In Figure 11 this is exemplified with two adaptation options, where adaptation option 1 is only linked to the first future time slice. For example, if an awareness campaign is implemented, the positive effects of such adaptation may only have a rather short temporal effect. Adaptation option 2 is linked to all time slices, as, for example, a structural measure can have a long technical life time.

4.3 Spatial dimension of risk and adaptation benefits

An additional challenge for improving the description of flood risk in an area is the inclusion of a spatial dimension to risk and adaptation benefits (Koks *et al.*, 2014). A spatial risk profile can be beneficial for identifying sub-areas where risk exceeds the acceptable level so that additional adaptation measures are needed, and for describing how the positive effects from adaptation measures are spread over different areas (Foudi, 2013). Hence, such spatial FRA provides relevant information for identifying areas that need to be adapted and for choosing the best adaptation measures for that purpose.

The Bayesian network approach can be used for spatial FRA. Any spatial resolution can be used for such an assessment, as for example, using a regular grid and asses risk for each grid separately. This thesis implements an approach, where the total area is divided into sub-regions to assess EAD separately on a sub-regional basis. When dividing the area into sub-regions, it is important that the risk is uniform within one sub-region. Otherwise, the sub-regional FRA may be biased, i.e. a region that shows low risk may include a small area that has a high risk.

In Figure 12 (below) the urban catchment is divided into five sub-regions as conducted in the case study in paper IV. The sub-regions have relatively similar size, and the risk is relatively equally distributed within the sub-regions. The ID (Figure 12, above) includes five impact nodes and EAD nodes, describing the risk explicitly for each sub-region. Total risk in the area is the sum of all sub-regional risks.

The effect of adaptation measures may also have a spatial scope according to the classification of adaptation made by Refsgaard *et al.* (2012). Consequently, some adaptation measures influence the impacts in all sub-regions, whereas others have very local influence. In the example in Figure 12, adaptation option 2 is linked to all five sub-regions. Adaptation option 1, on the other hand, is only relevant to sub-region 5.

The benefit from a spatial FRA allows for evaluating where, in an area, the need for adaptation is most urgent. By dividing a larger catchment into sub-regions, economic assessments may be conducted for each sub-region separately. Such a spatial CBA can provide decision-makers with valuable insight on how to prioritize adaptation options (Foudi, 2013).

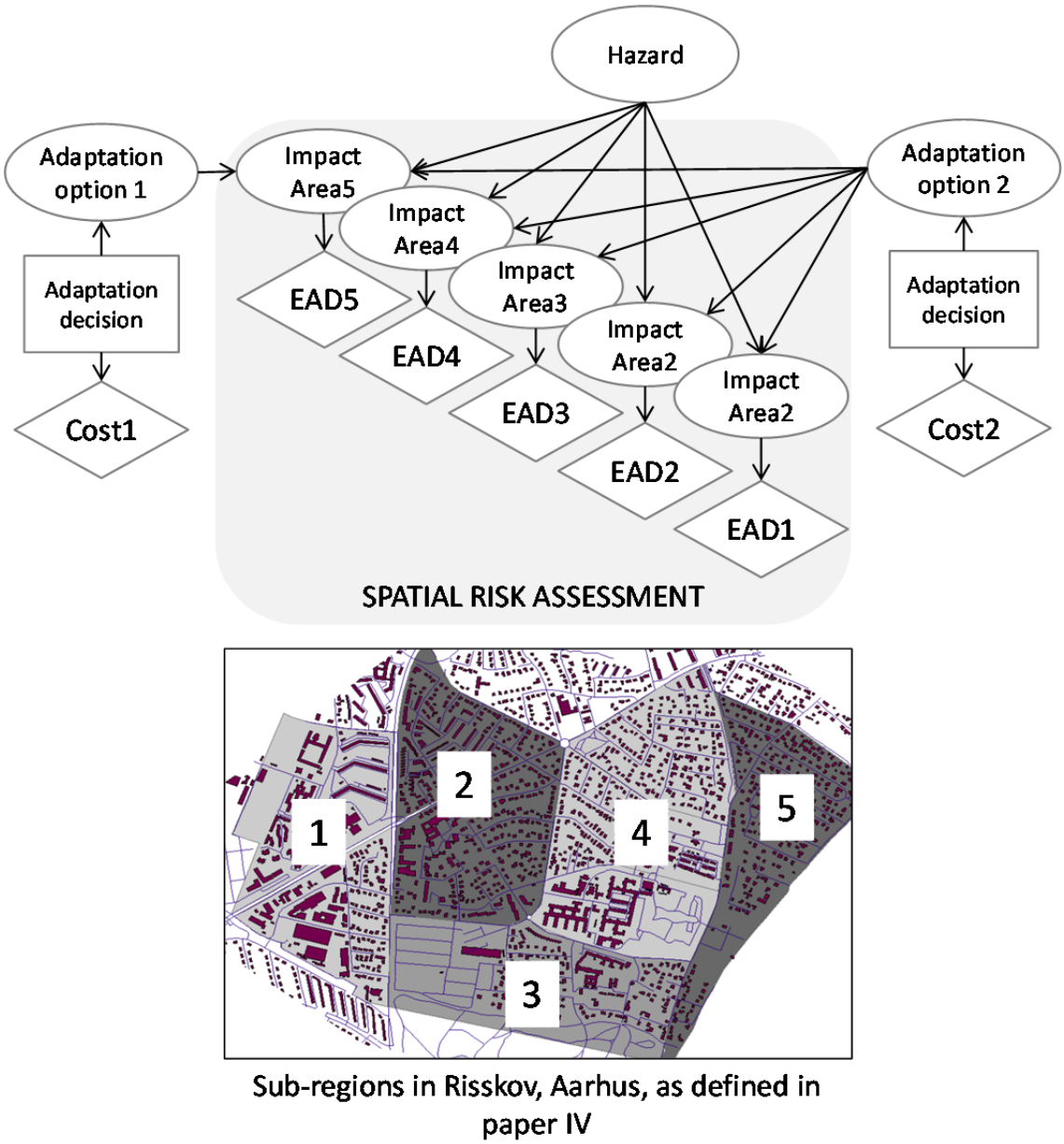


Figure 12. Top: An ID to assess the spatial distribution of flood risk. Bottom: an example of how an urban catchment can be divided into sub-regions. This example is from paper IV where a spatial FRA is conducted for Risskov, a residential area in Aarhus.

5 Flood risk assessment with multiple hazards

FRA methods generally only describe risk of one hazard, namely, the most threatening one. Several examples of risk assessment methods can be found in literature that focus on either pluvial flooding (Zhou *et al*., 2012), fluvial flooding (Wilby *et al*., 2007; Jonkman *et al*., 2008) or extreme sea surges (Hallegatte *et al*., 2011; Hall *et al*., 2006) individually. Single hazard FRA is considered acceptable because the most frequent hazard generally accounts for most of the expected damage, and because the probability of concurrent events is negligibly low (Pedersen *et al*., 2012).

Concurrent events refer to two or more flood hazards that occur simultaneously. In such circumstances the hazards may interact, and total damage from such a concurrent event may be larger than for the hazards separately. Figure 13 presents flood inundation maps for an urban catchment with a long coastline; a case study example presented in detail in paper IV. The flood maps show flood inundation for 1) a precipitation event with return period 100 yr, 2) a 2 m water level event, and 3) a combination of a 100 yr precipitation event and a 2 m water level event, i.e. a concurrent event. As shown, the concurrent event increases the flooded area in the entire catchment, also in areas far from the coast line. In this example, an extreme sea surge reduces the runoff capacity of drainage systems under heavy rainstorms, and, therefore, the damage from rainfall increases (Pedersen *et al*., 2012).

All hazards, whether they occur separately or simultaneously, contribute to total flood risk in an area. This is likely to become particularly challenging, because climate change is expected to affect the occurrence and magnitude of many different types of flood hazards. Precipitation is expected to increase in occurrence frequency and magnitude (Arnbjerg-Nielsen, 2012; Sunyer *et al*., 2009; Madsen, *et al*., 2009), and this may increase extreme discharges in river catchments and urban areas. Further, sea level rise and changes in storminess may increase the magnitude and occurrence of extreme sea surges (Woth *et al*., 2006). An increase in the occurrence frequency of many flood hazards simultaneously can potentially raise the contribution of a less frequent hazard to total risk and increase the probability of concurrent events.

In urban areas, many flood adaptation measures are structural and have a long technical life time (Zhou, 2012). If implemented today without accounting for the increase in total risk from all contributing hazards, we may eventually

find that the structures do not meet the desired service levels. Consequently, neglecting currently less frequent hazards in FRA may lead to considerable underestimations of flood risk in the future.

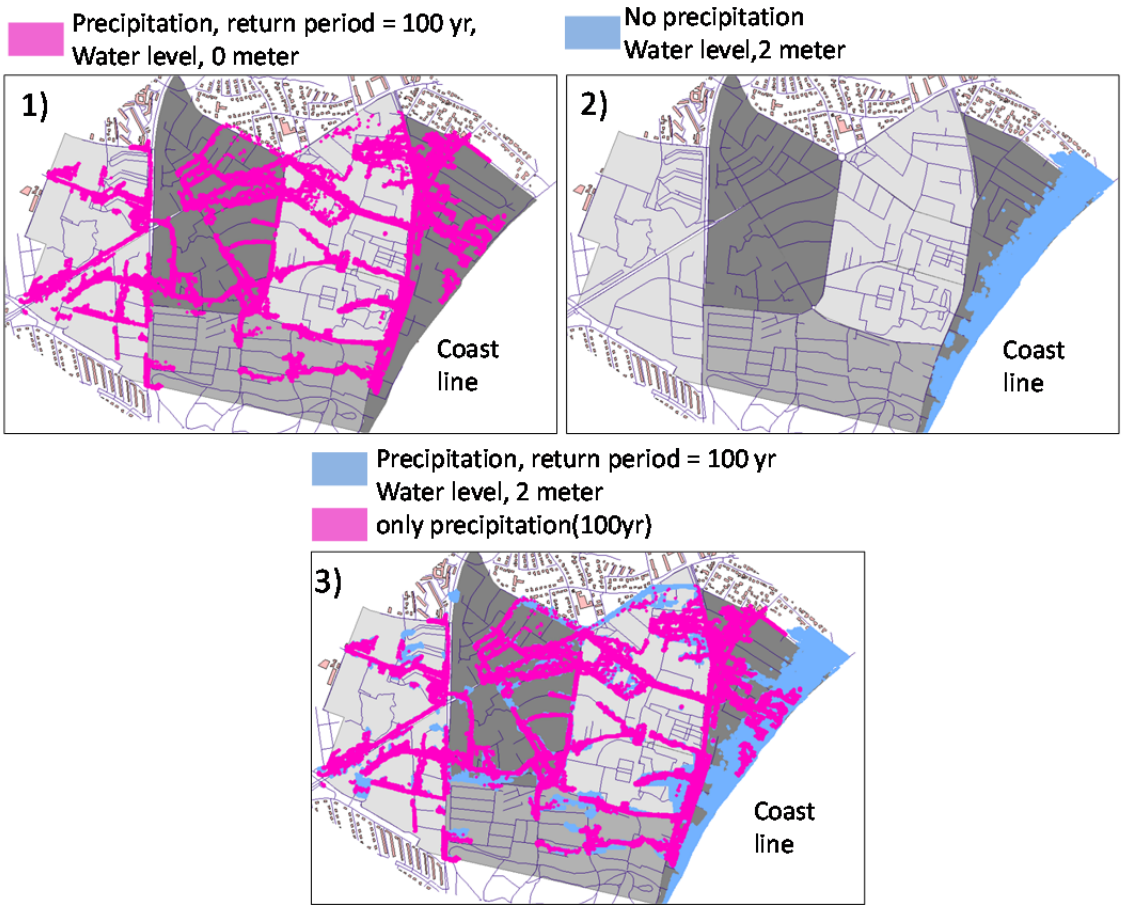


Figure 13. Flood inundation maps for Risskov, a residential area in Aarhus. The case study is presented in detail in paper IV. The maps show flood inundation for 1) precipitation event, return period 100 yr, 2) water level events, 2 m, and 3) concurrent events, precipitation return period 100 yr and water level 2 m.

FRA incorporating multiple hazards is a present day research topic, and only a few studies have been presented in literature (Jiang *et al*., 2013; Pedersen *et al*., 2012; Lamb *et al*., 2010). When multiple hazards are included in FRA, the analysis becomes more complex due to the simultaneous flood hazards that need to be described. The most common method for assessing the probability of concurrent events is to use multivariate statistical models (Lamb *et al*., 2010; Sunyer *et al*., 2009). These define a joint probability function of several hazard variables. For example, Pedersen *et al.* (2012) outlined a FRA method for floods caused by several hazards by means of the Copula method. The study indicated that concurrent events may become a great challenge in

adaptation planning, and incorporation of multiple hazards to risk assessments may be needed to assure appropriate adaptation

Although, initial studies on concurrent events suggest that it is important that these events are consider, actual analyses on such events are often difficult to conduct due to lack of observations on such events. Historical data series of hazard events are often not long enough to determine the probability of concurrent events (Pedersen *et al*., 2012). This can be overcome by developing artificial time series to describe the dependency between hazards (Pedersen *et al*., 2012). Another way to describe the expected impacts from multiple hazards is to use the BN method to FRA as presented in below.

5.1 An ID for assessing risk of multiple hazards

Figure 14 exemplifies an ID for assessing risk of multiple flood hazards, namely, extreme precipitation and sea water level events. Adaptation options, decisions and costs are linked to the impact node as presented in previous chapters.

To assess risk of multiple hazards, each hazard is described in an individual node. The input data to the hazard node is formulated as a daily probability density function (pdfs). Hence, for each hazard the pdf describes daily occurrence probability of all possible intervals of that hazard, and concurrent events are modelled by assuming that events are simultaneous, if they occur the same day. The CPT for the impact node is extended with pdfs describing the impacts for any possible combination of the two hazards. In the ID method, the combined effects of hazards are, therefore, described though the impact node. Hence, if the hazard occurrence can be described on a daily basis, the ID method for multiple events does not require an analysis of direct dependency between the hazards, but instead common effect causality (as presented in Figure 3) is applied to describe the simultaneous effects of the hazards though the impact node.

To describe hazards though daily pdfs, the method implicitly assumes that the dependence between flood hazards can be modelled through *climate dynamics*. This is exemplified in Figure 14 (only for one future time slice) with three nodes: *Season, Weather characteristics*, and *Future climate*. Hence, the climate dynamics component includes descriptions of both climate variability (exemplified as Season and Weather description node) and climate change (described in the Future climate node). The future climate node is included in

the network by linking it to the future hazard nodes (hazard nodes in future time slices) as presented previously in this thesis.

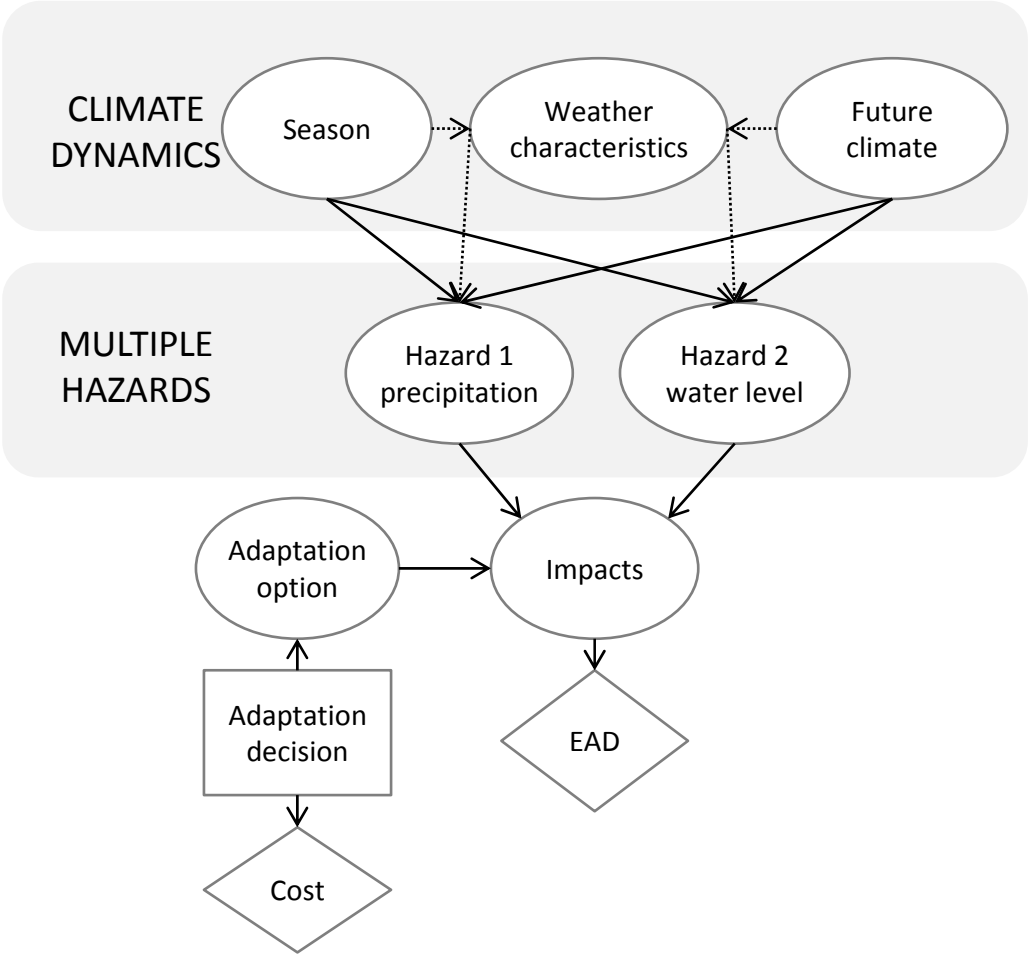


Figure 14. An ID for assessing flood risk of two hazards (sea water level and precipitation). This ID represents a future time slice. A present time slice would not include the Future climate node.

Climate variability describes how climate statistics vary over seasonal, annual and decadal time periods. Such variations may be important, especially when several hazards are assessed, because these variations may be correlated, whereby the probabilities of concurrent events are impacted (Pedersen *et al*., 2012). Hence, to model flood risk (EAD) in an ID, the focus is on describing annual variations in the occurrence probability of various hazards. For example, with regards to higher water levels and extreme precipitation events, there is a clear annual difference in the occurrence; extreme precipitation mainly occurs in summer months and high sea water levels in winter months as shown in paper II. Annual climate variability can thus be modelled through seasonal/monthly variations.

Climate variability can also be described though various weather characteristics, such as, for example, large-scale atmospheric circulations (Philipp *et al*., 2010; Huth *et al*., 2008) as described in the chapter 6, or regional climate oscillations, such as the El Niño southern oscillation (Rose & Massie, 2009), which is known to influence regional weather conditions. Weather characteristics included in the ID are described as individual nodes and are linked to the appropriate hazard nodes. Thus, the input data to the hazard node are extended to a CPT that includes pdfs of all possible combinations of the states of these climate dynamics nodes.

In addition, there may be internal relationships between the nodes in the climate dynamics component. For example, large-scale atmospheric circulation is known to have a seasonal variation (Schiemann & Frei, 2010), and this can be modelled by linking the season node with the node that describes atmospheric circulation, as presented in Figure 14. Further, some weather characteristics may be affected by climate change. For example, the occurrence frequency of large-scale atmospheric circulation patterns may change in the future (Lorenzo *et al*., 2011; Demuzere *et al*., 2009), and this can be modelled by linking the future climate node to the weather characteristics node. Hence, detailed climate dynamics modelling may require a rather complex network of nodes, where careful consideration needs to be given to the interactions among climate dynamics nodes themselves and with present/future hazard nodes.

6 Relationship between flood generating events and large-scale atmospheric circulation

As described in chapter 5, weather characteristics can be used to improve the description of flood generating hazards and there simultaneous occurrence. This chapter presents the research conducted towards describing the relationship between large-scale atmospheric circulation and flood generating hazards. The full study is presented in paper II.

6.1 Introduction

A major field within climatological research is relating weather to climate at local, regional, continental and global scales (O'Hare & Sweeney, 1993). Micro-climatic conditions, describing local fluxes of energy and moisture, are closely related to weather at very local scales. At regional /mesoscale, air stability plays an important role in describing weather. At the very largest, i.e. global scale, the aim is to describe the relationship between general circulation and weather. Between the meso- and global scale lies the sub-continental/continental scale, which relates weather to large-scale (also called synoptic) atmospheric circulation (Post *et al.*, 2002; Garavaglia *et al.*, 2010; Stehlik & Bárdossy, 2002).

Different circulation type classifications (CTCs) are commonly used to describe large-scale atmospheric circulation patterns. These classify circulation states into distinct groups (Philipp *et al.*, 2010) and are considered an important tool for analyzing a range of weather conditions (Jacobeit, 2010). However, classifications compress information into a catalogue, and this compression generally leads to loss of information. Hence, classifications can lead to difficulties in relating circulation types with the analyzed weather phenomenon (Philipp *et al.*, 2010). Consequently, there exists no generally accepted classification system, as CTCs are purpose-made simplifications rather than a physical reality (Huth *et al.*, 2008).

A large number of classifications are available today (Philipp *et al.*, 2010; Huth *et al.*, 2008; Schiemann & Frei, 2010), and careful consideration of the suitability of the chosen CTC is needed for any given application. The study presented in paper II uses the Lamb circulation type (LCT) classification for the assessment. The main objective here is to assess the relationship between

LCTs and flood generating events, and, hence, to identify ways to improve the description of the occurrence of flood generating events. An improvement in the description of how floods may occur can decrease the overall uncertainty related to hazard occurrence and, hence, improve FRA. The study analyses two flood hazards, namely, precipitation and sea surges in Aarhus, Denmark. Both hazards are considered threats, as such extreme events result in considerable flood damage in the area.

6.2 Lamb circulation type classification

The LCT classification was first developed by Lamb (1950) and later automated by Jenkinson *et al.* (1977). The LCT classification indicates flow direction and vorticity, and, hence, describes the prevailing pressure characteristic and indicates the presence of storms (Jenkinson & Collison, 1977; Jones, 2001). LCTs are calculated by means of circulation indices (Jones *et al.*, 1993) and classification rules (Jenkinson & Collison, 1977) as described in detail in paper II. For the computation of LCT, mean sea level pressure at 16 grid points around Denmark are needed (see Figure 15).

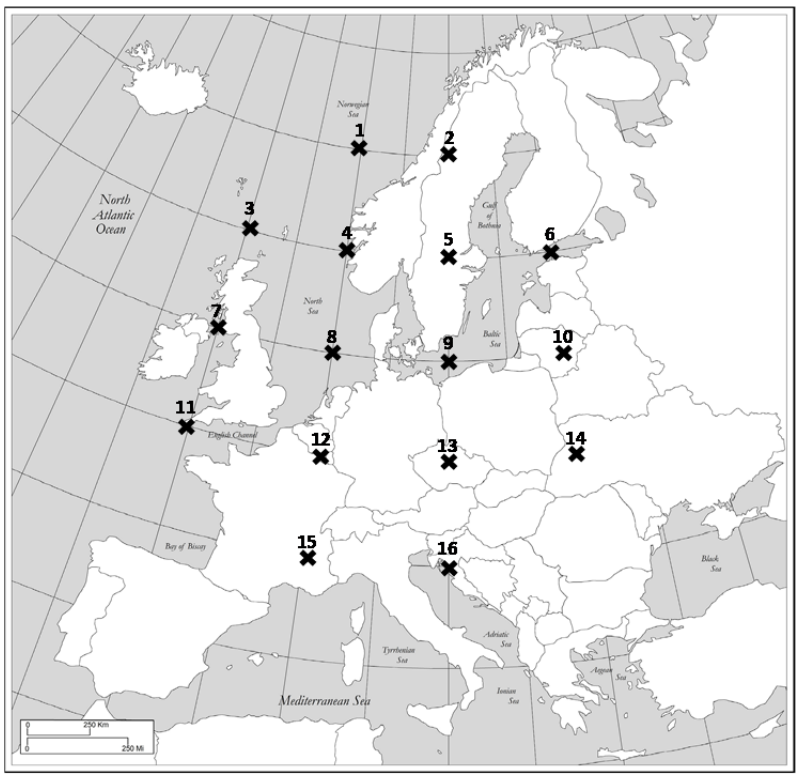


Figure 15. Grid points from which mean sea level pressure is extracted to calculate LCTs with Denmark in the centre.

There are several advantages in using a circulation type classification such as the LCT, for analysing weather characteristics. Firstly, they are easy to use. Every given day is assigned a specific LCT, and it is very straight forward to combine these daily LCTs with the daily maximum events (O'Hare & Sweeney, 1993). Secondly, LCTs can be calculated for any given region, if data of mean sea level pressure are available. Thirdly, the synoptic circulation that LCTs describe is, in theory, directly linked with a particular type of weather (O'Hare & Sweeney, 1993). Although specific weather conditions may be a result of more complex phenomena, the relationship between LCTs and weather is a descriptive way to identify regional weather characteristics, which may be useful in further applications, such as FRA.

The LCT classification has 26 types divided into 2 non-directional types (cyclonic (C) and anti-cyclonic (A)), 8 directional types (southerly (S), northerly (N), easterly (E), westerly (W)), and combinations of these, i.e. SE, SW, NE, and NW), and 15 hybrid types (the non-directional and directional type combined, for example CSE) (Jenkinson & Collison, 1977). Using the LCT classification for describing weather characteristics has a long tradition and has been widely used in various applications such as: precipitation (Post *et al*., 2002; Fernández-González *et al*., 2012; Linderson, 2001) and temperature analysis (Brown, 2003; Chen, 2000; Ramos *et al*., 2010), assessment of future atmospheric circulation frequencies (Lorenzo *et al*., 2011) and analysis of extreme river discharges (Pattison & Lane, 2012).

Some studies have chosen to group the LCTs to clarify the analysis and to obtain reasonable results in analyses with limited data (Trigo & DaCamara, 2000; Svensson *et al*., 2002; Twardoz, 2007; van den Besselaar *et al*., 2010). While such a grouping may be necessary for the application, this transformation may lead to further loss of information (Schiemann & Frei, 2010; Jacobeit, 2010). In paper II, LCTs are grouped as suggested by Trigo *et al.* (2000). They re-grouped the 26 LCTs into 10 Lamb circulation classes (LCCs), by including the hybrid types into the directional and non-directional types. Each of the 16 hybrid types are included to the corresponding directional and cyclonic/anticyclonic types with a weight of 0.5 (Trigo & DaCamara, 2000). For example, LCT *CNW* is included as 0.5 in *C* and 0.5 in *NW*.

Figure 16 presents the occurrence frequency of LCTs and LCCs over Denmark in time period 1979-2001. The anti-cyclonic (*A)* type has the highest frequency in both classifications. The second highest frequency is observed

for the westerly (*W*) direction in LCT classification and cyclonic (*C*) circulation in the LCC classification.

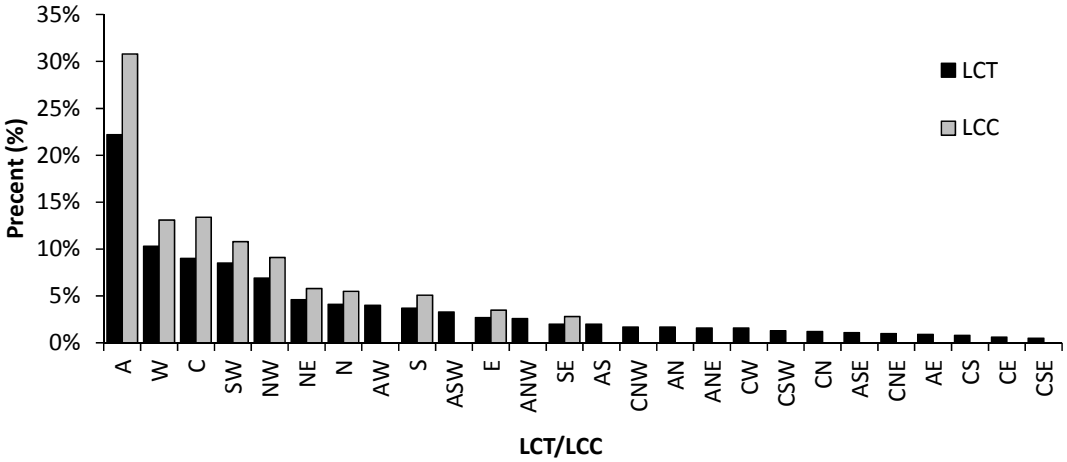


Figure 16. Occurrence frequency of LCTs and LCC over Denmark. Assessment based on precipitation data provided by the Water Pollution Committee of The Society of Danish Engineers (SVK) for the time period 1979-2001 (23 years) for precipitation gauging station 5517 in Aarhus, Denmark, and water level data for Aarhus harbour were provided by the Danish Meteorological Institute for the time period 1979-2001.

6.3 Significant occurrence of flood generating events in Aarhus

The relationship between the LCTs/LCCs and flood generating events (precipitation and sea surges) is described by identifying statistical significance (significantly high/low occurrence). The method is described in detail in paper II. Here, only the results from the LCC analysis are presented as the original study showed that the LCC and LCT classification provided very similar results.

For precipitation and water level events, the threshold levels 20 events/year, 5 events/year and 1 event/year are used in the analysis. Precipitation events are described as maximum daily 3 hourly precipitation to correspond to the concentration time of the analysed urban catchment. Water level events are described as maximum daily events. The choice of thresholds, and hence data sample size for the extreme value analysis, is a question of assuring a sufficient amount of events for the analysis and of representing a suitable range of high precipitation and water level events. Due to the relatively short observation period of the data used in the analysis (i.e. 23 years), 20 events/year is used to provide a larger data set for a more robust analysis. Using 1

event/year, on the other hand, provides a more accurate description of relevant extreme events with the drawback that there are very few observations included in the analysis. Overall, the assessment using several thresholds allows for evaluation of the consistency of the result over different thresholds.

The results are presented in Table 2. HIGH refers to significantly high occurrence of precipitation and water level events, and LOW to significantly low occurrence. Green cells describe LCCs with higher occurrence of precipitation events than expected (but not statistically significantly high), and red similarly refers to lower than expected occurrence.

Table 2. Overview of which LCCs have high and low occurrence of precipitation and water level events. HIGH/LOW refers to significant occurrence. Green without text describes high, but not significant, occurrence and red without text describes low, but not significant, occurrence of hazard events.

	PRECIPITATION			WATER LEVEL		
	20 events/year	5 events/year	1 event/year	20 events/year	5 events/year	1 event/year
A	LOW	LOW				
W	HIGH			HIGH	HIGH	
C	HIGH	HIGH		LOW		
SW	HIGH	HIGH		HIGH	HIGH	
NW	HIGH					
NE	LOW	LOW	LOW	LOW	LOW	
N	LOW				LOW	LOW
S			LOW			
E	LOW	LOW	LOW	LOW	LOW	LOW
SE	LOW	LOW	LOW	LOW	LOW	

The main results from the analysis on relationship between LCCs and hazard events are:

- Precipitation events show significantly high occurrence in *W, C, SW,* and *NW*. These LCCs have a consistently high occurrence (green) over all thresholds. Significantly low occurrence of precipitation events is observed for *A, NE, N, S, E* and *SE*, and these LCCs, expect for *N*, have consistently low occurrence over all thresholds.
- Water level events show significantly high occurrence for *W* and *SW*, and this is consistent over all thresholds. Significantly low occurrence

for water level events is obtained for *C, NE, N, E, S*, and *SE*, and this is consistent over all thresholds. LCCs *A* and *NW* are not consistent over the different thresholds.

- Both precipitation and water level events show significantly high occurrence of events for LCCs *W* and *SW*. This could indicate that some LCTs can cause both high precipitation and water levels, and, hence, days with these LCCs may have a higher probability for concurrent events.
- Similarly, LCCs *NE, E,* and *SE* show significantly low occurrence for both precipitation and water level events, and this could indicate that there is a lower probability for concurrent events during days with these LCCs.

The study also analysed significant occurrence of simultaneous precipitation and water level events using the threshold 20 events/year. The result is presented in Figure 17. The result shows that LCC *W* has significantly high occurrence of concurrent events, and *A* has significantly low occurrence of concurrent events. No concurrent events are observed for LCCs *NE, N, E* and *SE*. This result is in agreement with the analysis conducted for the two flood hazards separately and presented in Table 2.

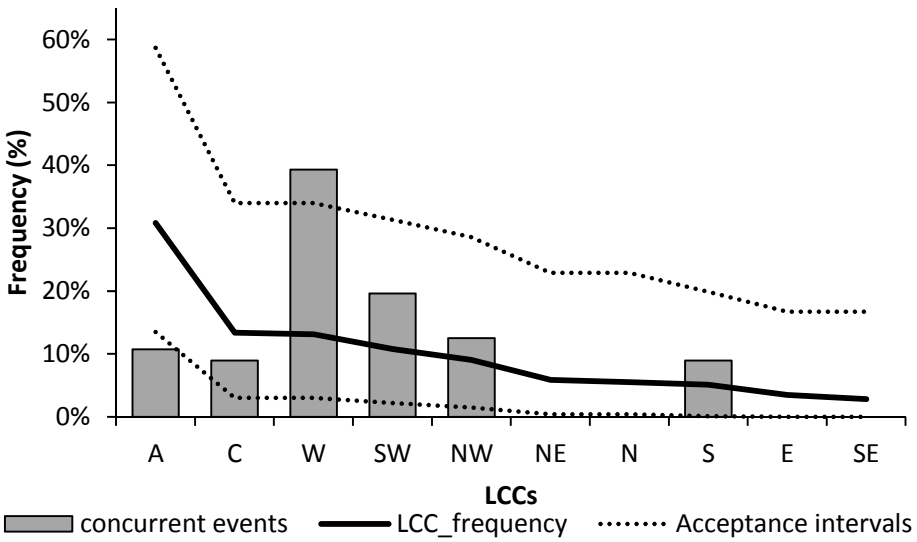


Figure 17. The bars represent frequency of concurrent events for each LCC in Aarhus (1979-2001). The black solid line shows the occurrence frequency of LCCs (1979-2001), and the dashed lines represent acceptance intervals for concurrent events using the threshold 20 events/year for precipitation and water level events.

7 Spatio-temporal flood risk assessment for multiple hazards, case study: Risskov, Aarhus

This chapter summarizes a case study conducted in a residential area, Risskov, in Aarhus. The ID, which is presented in Figure 18, is based on the methodological framework presented in chapter 3.1 and includes multiple hazards as illustrated in chapter 6. The method is extended with multiple adaptation options as presented in chapter 4.1, a temporal dimension as described in chapter 4.2, and a spatial risk profile according to the method presented in chapter 4.3. The derivation of input data for the different nodes is described in detail in paper IV.

7.1 Method

The ID in Figure 18 is divided into following components:

1. *Spatial Risk assessment with multiple hazards*: Two hazards, precipitation and sea water level, are included into the ID. The two hazards are initially dependent on the season. Detailed pdfs for the hazard nodes are presented in paper IV.

   The spatial dimension of risk is assessed by dividing the area into five sub-regions. The included impacts categories (buildings, basements, roads, sewers, stores, and heath) are all described in monetary terms and are combined into one impact node for each sub-region, which is utilized to assess the sub-regional EAD. The impact assessment and EAD calculations are illustrated in chapter 3.1. The specific unit costs and critical thresholds for the impact assessment are described in paper IV.

2. *Temporal adaptation assessment*: The temporal dimension of risk is modelled with four time slices; 2015, 2025, 2065, and 2105. In this case study two structural measures are tested; 1) a drainage system improvement and 2) construction of a floodwall, including the combination of these. The cost of drainage implementation is 24 million DKK and for floodwall 49 million DKK.

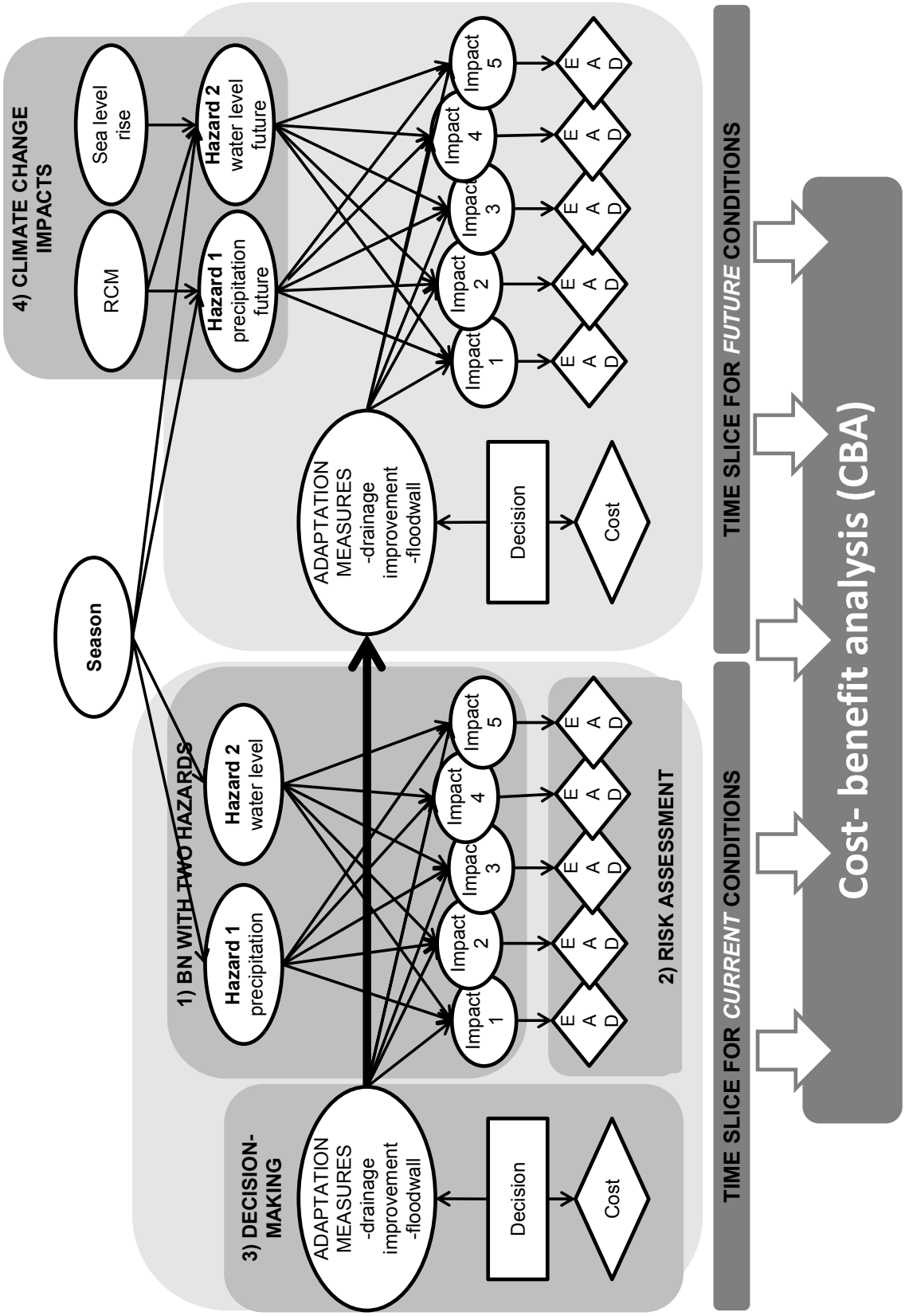


Figure 18. An ID for spatio-temporal FRA with multiple hazards. The ID is divided into 3 parts: 1) Spatial FRA with multiple hazards, 2) Temporal adaptation assessment, and 3) Climate dynamics description. The result from the ID is integrated with a CBA

3. *Climate dynamics description*: Climate variability is described by connecting a Season node to the Hazard nodes in all time slices. Climate change is modelled with two nodes: 1) Change in future frequency of extremes, which describes the change assessed from RCM data, and 2) Sea level rise, which describes the expected sea level rise in Aarhus. The climate change nodes are linked to hazard nodes in future time slices.
4. *Cost-Benefit Analysis:* The FRA is integrated with a spatial CBA, and NPV is used as decision criteria to identify the adaptation measure that has the highest net benefits. For the spatial CBA, change in EAD between the time slices is assumed to be linear, and the cost of adaptation is divided equally between each sub-region.

7.2 Results

Figure 19 presents 1) EAD with both hazards, 2) EAD for the hazards (precipitation and water level events) separately, and 3) EAD from concurrent events exclusively. Figure 20 presents EAD with and without adaptation implementation.

In Risskov, total undiscounted added damage from climate change is 972 million DKK without adaptation. Of this, 74% of caused by only precipitation events. Water level events account for 17 % of all undiscounted damage and concurrent event, consequently, account for 9 % for total undiscounted damage. The overall conclusion from the FRA is, hence, that the inclusion of water level events to the FRA increases the damage considerably and that concurrent events account for a notable part of the added damage costs. To improve FRM processes in Risskov and for identifying optimal adaptation, it is, therefore, important to introduce multiple hazards into FRA.

At sub-regional level the temporal risk profiles vary considerably. In sub-region 1 and 2 high sea water levels have a negligible impact on EAD, and, hence, total all damage in these sub-regions is almost entirely a result of precipitation extremes. In sub-region 3, 4 and 5 high sea water levels increase EAD over time. Concurrent events account for 5%, 7% and 10%, respectively, in these sub-regions.

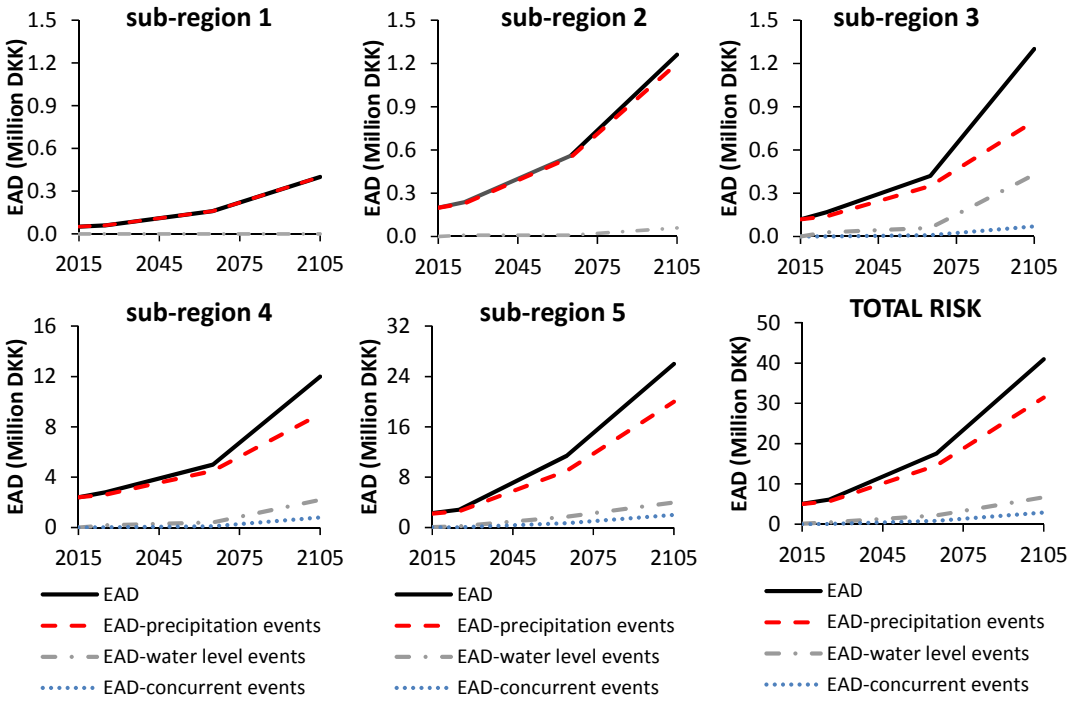


Figure 19. A spatio-temporal FRA without adaptation implementation for Risskov, Aarhus. EAD is presented for: 1) EAD with both hazards, 2) EAD for the hazards (precipitation and water level events) separately, and 3) EAD from concurrent events exclusively.

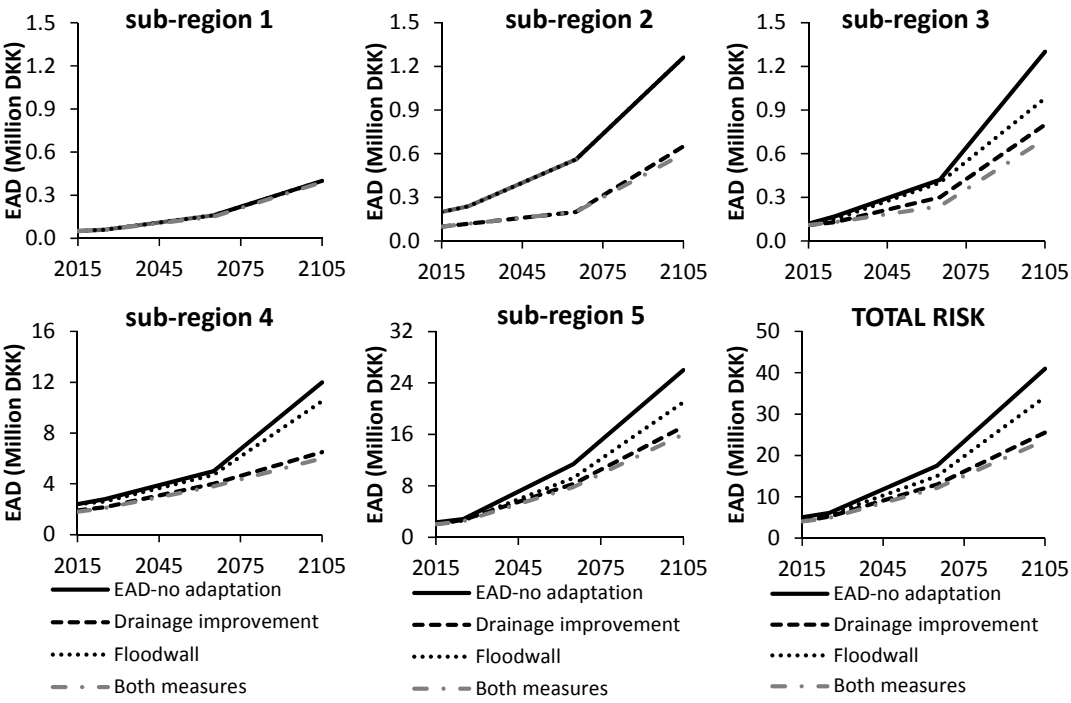


Figure 20. FRA with adaptation implementation in Risskov. Adaptation measures drainage system improvement, floodwall construction and a combination of both measures are tested in the FRA.

The drainage improvement decreases total EAD to 25.5 million DKK (38 % decrease) in 2105 in Risskov. Similarly, a floodwall results in 34 million DKK (i.e. a 17% decrease) in 2105. A combination of both measures provides the largest reduction in flood risk, to 24 million DKK (42% decrease).

In sub-regions 1 and 2, the floodwall has no effect on EAD. In sub-region 2, the drainage improvement decreases risk considerably. In sub-region 3, 4 and 5 both adaptation measure decrease EAD. In sub-region 3 the drainage improvement decreases EAD in 2105 with 38 %, in sub-region 4 with 46 % and in sub-region 5 with 34 %. The floodwall construction decreases risk in sub-region 3 with 25 %, in sub-region 4 with 13 % and in sub-region 5 with 19% in 2105. A combination of both measure results in the largest decrease; 46% in sub-region 3, 50% in sub-region 4 and 38% in sub-region 5.

Table 3 presents the result from the spatial CBA, i.e. the NPV for adaptation implementation in 2015, 2025 and 2065. The CBA utilizes EAD to year 2015 as the FRA does not provide information of how EAD changes after this year. Therefore, the CBA assesses NPV for adaptation over the next 90 years regardless of the time of adaptation.

Table 3. A spatial CBA in Risskov. Net present values (NPVs) are calculated for implementation of adaptation options drainage improvement, floodwall, and a combination in time slices 2015, 2025 and 2065. It is assumed that the overall implementation costs are divided equally over each sub-region. Red represents negative NPVs. Bold values are the highest, and, therefore, the optimal option in each time slice and sub- region.

		Cost (million DKK)		2015			2025			2065		
		Drainage	Flood wall	Drainage	Floodwall	Both	Drainage	Floodwall	Both	Drainage	Floodwall	Both
	Risskov	24.1	34	***57.8***	4.2	37.6	***56.6***	12.4	44.2	***35.3***	12.1	33.2
sub-region	1	4.82	6.8	***-4.8***	-6.8	-11.6	***-3.6***	-5.1	-8.6	***-1.1***	-1.6	-2.7
	2	4.82	6.8	***1.6***	-6.8	-5.2	***2.0***	-5.1	-0.3	***1.2***	-1.6	-0.3
	3	4.82	6.8	***-2.4***	-18.2	-8.6	***-1.3***	-14.1	-5.7	***0.1***	-4.1	-1.1
	4	4.82	6.8	***24.5***	0.6	21.6	***21.4***	2.3	19.5	***11.1***	1.9	11.0
	5	4.82	6.8	38.9	23.0	***41.2***	38.0	24.4	***41.9***	24.0	14.3	***26.1***

The largest NPV for Risskov is obtained for drainage system improvement in 2015. Floodwall construction also obtains a positive, but lower NPV if implemented in 2015. NPV for floodwall construction is highest in 2025. Implementation of both adaptation measures provides the highest NPV in 2025.

Therefore, a CBA for Risskov suggests that the drainage improvement should be implemented presently and the floodwall construction could be re-considered in the near future.

We assume that the implementation costs are divided equally between sub-regions. In sub-region 1 NPV is negative for all adaptation options. In sub-region 2 the drainage system improvement provides a positive NPV. Sub-region 3 obtains a positive NPV only in 2065 for drainage system improvement. In sub-region 4 all adaptation possibilities provide a positive NPV, but a drainage system improvement has the highest NPV and NPV for the floodwall is very low. In sub-region 5 the highest NPV is calculated for implementing both measures presently. Consequently, the spatial CBA suggest that sub-region 1 and 3 have currently no interest in investing in flood adaptation. Sub-regions 2 and 4 have an interest in investing in drainage improvement presently. Sub-region 5 prefers both adaptation measures.

8 Discussion and conclusions

FRAs are an essential part of FRM as they provide flood management practitioners with crucial information for robust decision making. In the light of the challenges in FRA raised in this thesis, this chapter discusses the role of IDs for improving FRA to contribute to improved FRM practices.

Integration of disciplines and data sources

FRA requires integration of a wide range of different disciplines. However, due to lack of common theories, concepts and language cooperation between scientists from different fields are challenging. Studies have concluded that conceptual models may ease the process of finding a common language and identify common goals (Heemskerk *et al.*, 2003).

The graphical description of an ID can provide conceptualization of a problem that is needed for efficient integration of different disciplines. For example, to construct the ID for FRA, as presented in this thesis, basic concepts from several disciplines are needed; earth science (extreme events), atmospheric science (circulation types), structural engineering (structural adaptation measures), geoinformatics (impact assessments), decision theory (adaptation decisions), socio-economics (CBA), oceanography (sea level rise) etc. Consequently, IDs are omindiciplinary in the sense that they can handle and combine information from all possible disciplines, provided that the information can be presented in a format suitable for an ID. However, an interdisciplinary approach to define the ID structure can also be difficult, as experts can have large disagreements on which variables that are important to include (LandscapeLogic, 2009).

In addition, IDs are also extensively used for modelling systems using a wide range of data and information sources; everything from complex statistical analyses and models to expert opinions can be used in an ID. Hence, one of the great potentials of IDs is the flexibility in combining various data in a transparent and robust manner, to provide a mathematically coherent FRA.

Communication between scientists and decision-makers

As previously described in this thesis, FRA traditionally applies mathematical methods, which may be difficult to communicate to decision-makers, who lack the required scientific background. In such cases, an ID can be a preferable method. It may be less important that decision-makers understand the

mathematical descriptions of the data analysis, while it is crucial that they gain an overall understanding of the system where risk occurs and where decisions have to be made.

The FRA outlined in this thesis, is manly developed to provide decision-support, i.e. to provide information that can aid decision-makers to develop robust adaptation plans. The method provides a transparent spatial and temporal risk profile, which may be of great advantage in decision-making. With regards to adaptation assessment, the method may be utilized to systematically test the benefits from various adaptation options and combinations of these. Both, the temporal benefits, i.e. the best time to implement an adaptation option, and the spatial benefits, i.e. which areas need adaptation and which adaptation options can provide that, can be tested in an ID.

Accuracy increases complexity

The aim of FRAs is to provide an accurate and clear description of flood risk. However, in reality flood risk and adaptation benefits are not a closed system. Instead, there are plenty of interactions in the society that increases the complexity for decision-makers. For example, the benefits from adaptation options may not solely decrease the flood risk. Some adaptation options may introduce further socio-economic benefits, as for example increase in property value in an area (Zhou *et al.*, 2013). In addition, the impact assessment, which in this thesis to a considerable extent focuses on direct impacts, may in reality introduce further chain reactions of impacts. If one impact occurs, it may increase the probability of others. In theory these complex interactions between different impacts can be modelled in an ID, and a wide range of benefits from adaptation can be included. However, this all increases the complexity of the assessment.

Inclusion of all possible impact and adaptation options increase the complexity of the system extensively. This will, potentially, reduce the usability of the graphical layout of the ID to communicate FRA results. In addition, although we may find that chain reactions between impacts occur, it may in practice be rather difficult to model such reactions correctly due to lack of knowledge of the causality between the impacts.

Further, increased complexity increases the data requirements. One might argue that it is desirable to include all benefits and impacts, but the amount of information and the data analysis required for such accuracy, may, firstly, be overwhelming, and, secondly, introduce a tedious task for the modellers. Not

to mention that in practice it may be next to impossible to attain accurate information of variables and interactions between these. Consequently, as one of the great benefits of an ID is the flexibility to include all causalities in the system, this may also become a weakness without careful considerations of the needed extent of the network and the desired accuracy of the assessment.

With regards to assessing risk from several hazards, there is a need to find means to describe the occurrence of the various hazards. Seasonal or monthly variability can currently be used for describing the annual variations in hazard occurrences, but there are possibilities in including weather descriptions to the FRA to improve the hazard occurrence description. The relationship between large-scale atmospheric circulation and hazards is described in this thesis. Although, the study could show that some circulation types have a significantly high occurrence of events, the result of the analysis is not robust enough to be utilized in FRA. Hence, there is still considerable possibilities to increase the accuracy of hazard occurrence and, hence, the accuracy of FRAs.

Uncertainty

Analyzing uncertainty in FRA is often considered a requirement for robust assessment. However, studies have implied that decision-makers have, compared to scientists, very different perspectives with regards to uncertainties (Morss *et al*., 2005; Faulkner *et al*., 2007). Overall, decisions are constantly made under uncertainty, i.e. it is an everyday task for those involved in decision-making, and the scientific uncertainties are only a small part of the entire uncertainty spectrum.

Hence, it seems logical that from a decisions-making point of view, it may not be essential to obtain an all-inclusive understanding of the complexity in assessing scientific uncertainties and the methods behind such analyses. Instead, previous studies have recognized that decision-making practices would profit from explicit descriptions of the scientific uncertainties Morss *et al*., 2005, and from descriptions on how these uncertainties may affect the overall outcome of the FRA. An ID describes uncertainty explicitly for each chance node through probability distributions, and with such explicit descriptions quite complex issues may be efficiently communicated to decision-makers.

On the other hand, studies have suggested that decision-makers, rather than requesting extensive uncertainty descriptions, are in need of accurate information to support their decision process (Morss *et al*., 2005). The method in

this thesis, while it may present the underlying uncertainties of the different variables, describes risk as one point value, i.e. EAD or other risk unit. This value reflects the best guess that one can make based on the information available for the assessment. Assuming that the system is described correctly in the ID with sufficient details of hazards and their impacts and using best available information/data of the variables, the overall conclusion is that the risk unit assessed in an ID provides the most accurate description of risk that currently is available.

9 Future research

Input data

FRAs based on IDs are only as good as the utilized input data. There is a considerable need and ongoing interest in the scientific community to improve the data analysis for different parts of FRA. With regards to hazard analysis, improving especially the description of local occurrence of flood hazards and change in occurrence over time as a result of climate change impacts is an essential part of reducing the uncertainty of the temporal risk profile. The ID approach for FRA would greatly benefit from studies that aim at developing hazard pdfs and pdfs describing the uncertainty of the pdf parameters.

Further, studies focusing on relationships between local weather and larger climatic phenomena are a requirement for improved hazard descriptions. For example, large-scale atmospheric circulation may introduce a possibility to describe the hazard occurrence better, and such relationship should be further explored. In addition, combining local weather with large climate patterns, may introduce new possibilities for understanding and describing concurrent events. For FRA with multiple hazards there is a clear need to find new means to describe concurrency of events.

With regards to impact assessments, GIS approaches provide possibilities to describe the spatial distribution of negative consequences of flooding. The impact assessment conducted in this research is based on unit costs of assets and critical thresholds that describe when the asset is flooded. These unit costs and critical thresholds are uncertain, and the impact assessment can be improved by including an uncertainty description of these parameters. Hence, impact assessments need more detailed stage-damage curves and uncertainty bounds for the FRA to describe risk more accurately.

To improve the applicability of IDs to FRA, there are also interesting possibilities in integrating IDs with for example GIS models to automatically obtain impact data for the assessments. Hence, there is a possibility the develop IDs further into an actual tool to be used by flood risk modellers.

Flood risk at different scales

This thesis focuses on FRA in urban areas. Alongside, the ID is suitable for FRA on different scales. For example, FRA for an entire river catchment could benefit from using the ID approach. FRA for large catchments have

clear similarities with integrated water resources management (IWRM); the complex interactions and expectations between a wide range of stakeholders, industries and communities along the river and the aim to identify plans that are economically beneficial while socially equitable. The ID could be used to identify the suitable adaptations along a river that best meet the expectations of all involved.

In addition, IDs can be utilized for the assessment of very specific issues. Such could be the detailed analysis of dam breaks or detailed risk assessments on crucial infrastructure such as bridges.

Stakeholder involvement

In ecological and water resources management utilizing IDs in stakeholder involvement has proved beneficial. In climate impact and risk assessments such studies are not yet available. Robust adaptation plans require that the society accepts the plans and in FRA the possibility to use IDs as means to involve stakeholders could introduce new potentials for identifying suitable and acceptable adaptation options.

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11 Papers

I H. Åström, P. Friis Hansen, L. Garré, K. Arnbjerg-Nielsen, 2014. *An influence diagram for urban flood risk assessment through pluvial flood hazards under non-stationary conditions*. Journal of Water and Climate Change, 5 (3), pp. 276-286. doi:10.2166/wcc.2014.103

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IV H. Åström, H. Madsen, P. Friis Hansen, D. Rosbjerg, K. Arnbjerg-Nielsen. *A spatially distributed and non-stationary urban flood risk assessment methodology for multiple hazards using a Bayesian Influence diagram.* Submitted manuscript (Journal of Hydrology)

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

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The Department of Environmental Engineering (DTU Environment) conducts science-based engineering research within four sections:
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The department dates back to 1865, when Ludvig August Colding, the founder of the department, gave the first lecture on sanitary engineering as response to the cholera epidemics in Copenhagen in the late 1800s.

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