# Cascading effects and critical infrastructure

## Methods, challenges, and implications

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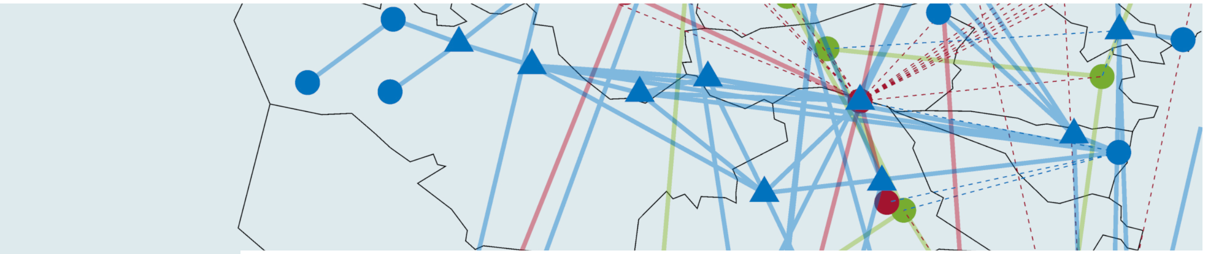

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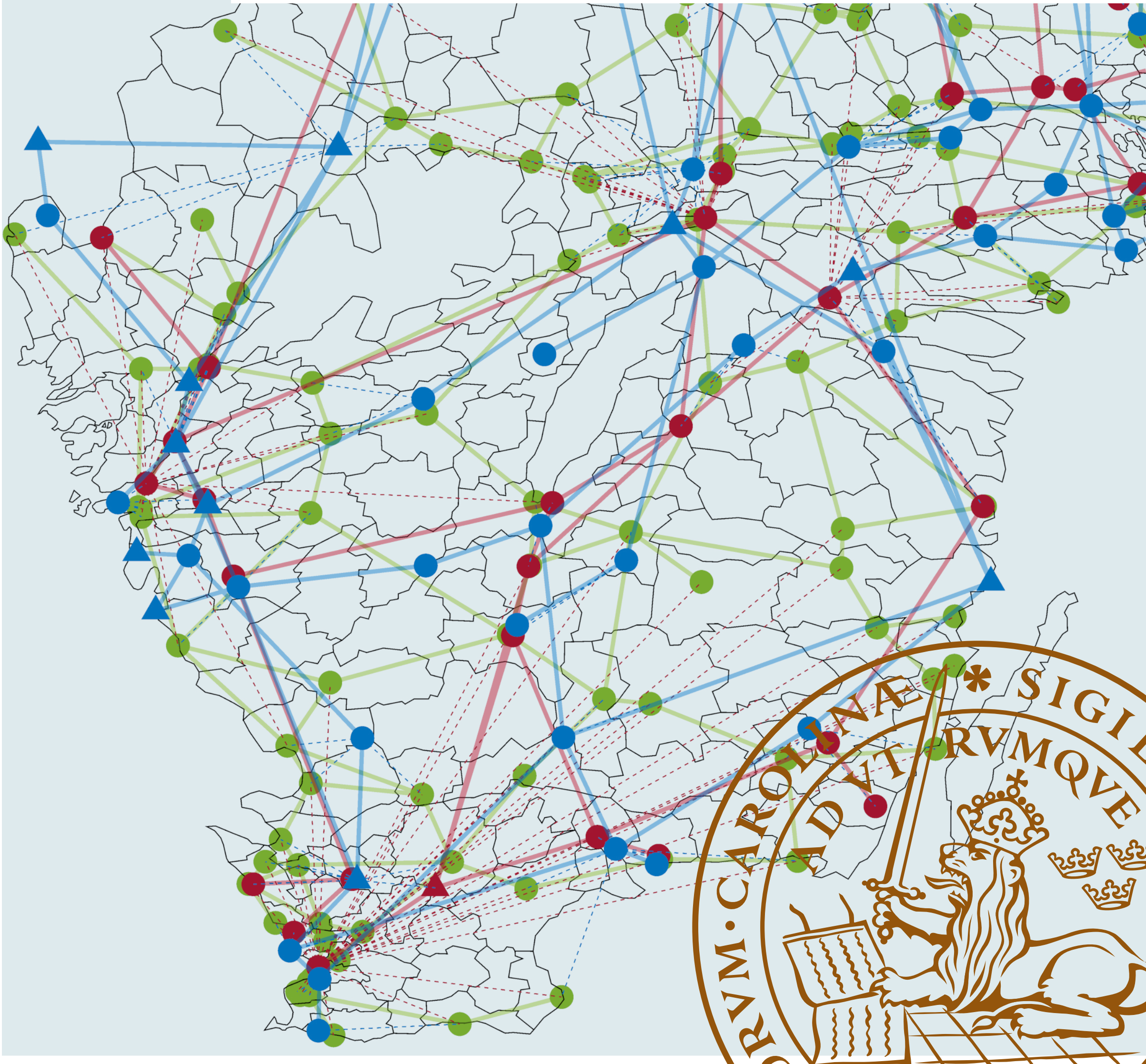
BJÖRN ARVIDSSON

FACULTY OF ENGINEERING | LUND UNIVERSITY

Cascading effects and critical infrastructure – Methods, challenges, and implications

# Cascading effects and critical infrastructure

## Methods, challenges, and implications

Björn Arvidsson

LUND
UNIVERSITY

DOCTORAL DISSERTATION

Doctoral dissertation for the degree of Doctor of Philosophy (PhD) at the Faculty of Engineering at Lund University to be publicly defended on 14th of June 2024 at 13.00 in lecture hall V:A, LTH.

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**Abstract:**

Cascading effects, arising from intricate interactions among vital social and technical infrastructures, are essential to consider when assessing the societal impacts of various disruptions caused by, for example, natural hazards, climate change, and antagonistic attacks. Critical Infrastructures (CIs) form the backbone of society, and their interdependent nature amplifies the risk of cascading effects. To analyse and mitigate large-scale disruptions in CIs, numerous countries and organisations, including Sweden and the European Union, have implemented several resilience management programs and policies.

This thesis aims to enhance understanding and methodologies for analysing cascading effects across interdependent CIs, particularly within the context of the Swedish implementation of EU directives. Employing various methods such as scoping studies, qualitative content analysis, and vulnerability analysis, the research reveals both scientific and practical gaps in the consideration of cascading effects. The findings reveal an immature consideration of cascading effects in assessments in Sweden related to flood risk management and that CIs are frequently treated in isolation, hindering the identification of interdependencies and analysis of cascading effects. Challenges include a lack of feasible analysis methods, data accessibility issues, national security and confidentiality considerations and resource constraints.

To address these challenges, the thesis proposes a simplified yet robust method (AB-CEM) aiding risk analysts and crisis managers in identifying interdependencies and cascading effects. It also advocates for a coordinated national initiative to gather CI data and establish secure data-sharing platforms alongside explicit guidelines for handling sensitive data and an empirical library of cascading effects accounts.

The thesis explores and emphasises the importance of considering cascading effects in risk, vulnerability and resilience assessments to ensure comprehensive identification and mitigation of potential risks and vulnerabilities. Ignoring these effects could lead to significant consequences being overlooked, particularly in severe scenarios. Thus, integrating cascading effects into assessments, incentives and governance structures is crucial for effective governance and resilience-building efforts.

**Keywords:** Cascading effects, Critical infrastructure, Resilience, Risk, Vulnerability, Flood, Governance, GIS

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# Cascading effects and critical infrastructure

## Methods, challenges, and implications

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# Summary

Cascading effects are negative consequences that arise from complex interactions between critical social and technical systems in society. Understanding and accounting for cascading effects is essential for assessing the societal impacts of natural hazards, climate change, supply chain disruptions, ecosystem disruptions or antagonistic attacks. One of the main reasons for cascading effects is the interdependent nature of Critical Infrastructures (CIs) that supply our society with, for example, energy, water, food, transportation, communication, healthcare, and security.

As it is undesirable to have large-scale disruptions in critical infrastructures, many countries and organisations have established risk management programs and policies. Sweden and the European Union are among them. These programs and policies involve conducting risk and vulnerability assessments to identify potential events or vulnerable components that could cause disruptions and estimate their possible consequences. However, according to several studies, Swedish risk and vulnerability assessments rarely consider cascading effects. Therefore, it is important to investigate the current practices of considering cascading effects and the potential challenges that Swedish governmental agencies and CI operators face.

The overall research aim of this thesis is to contribute knowledge and methods that can be used to support analyses of cascading effects across interdependent CIs. To reach this aim, cascading effects have been studied using various methods in the context of the Swedish implementation of the European Union Floods Directive and the Directive on the resilience of critical entities (CER Directive). The methods used include a scoping study, qualitative content analysis, article keyword analysis, workshops, interviews, vulnerability analysis, modelling, and simulation.

One of the main findings is that Swedish risk and vulnerability assessments have an immature consideration for cascading effects even though involved actors are aware of their importance. Additionally, CIs are often treated as stand-alone systems, making it difficult to identify cascading effects. Including cascading effects in flood risk management plans is progressing slowly. The thesis also identifies challenges for the actors in assessing cascading effects in risk and vulnerability assessments. These include a lack of feasible methods to analyse interdependencies, difficulty accessing necessary data, confidentiality concerns, limited resources and time and unclear benefits versus costs.

To overcome some of these challenges, a method (AB-CEM) was developed in this thesis to assist risk analysts in identifying and analysing interdependencies and cascading effects. The method was designed to be a simpler yet scientifically

grounded alternative for professionals compared to the methods presented in scientific literature. Another critical step towards improving the conditions for risk professionals to assess cascading effects is to make a coordinated, national initiative to gather CI and interdependency data. To disseminate this data to relevant stakeholders, it is also necessary to establish secure platforms for sharing sensitive CI data. Additionally, having more explicit guidelines for handling confidential data would support regional flood risk professionals working with sensitive data. An empirical library of documented accounts of cascading effects could also assist risk professionals.

The thesis emphasises the importance of considering cascading effects in resilience-oriented assessments to ensure comprehensive identification and mitigation of potential risks and vulnerabilities. If cascading effects are ignored, many potential societal impacts could remain unaccounted for, especially for the more extreme scenarios. Thus, integrating cascading effects between critical infrastructures into assessments is crucial for effective governance and resilience-building efforts.

# Sammanfattning

Kaskadeffekter är negativa konsekvenser som uppstår till följd av komplexa interaktioner mellan kritiska sociala och tekniska system i samhället. Att förstå och redogöra för kaskadeffekter är avgörande för att bedöma samhällseffekterna av naturkatastrofer, klimatförändringar, störningar i leveranskedjor, störningar i ekosystem eller antagonistiska attacker. En av de främsta orsakerna bakom kaskadeffekter är ömsesidiga beroenden mellan de kritiska infrastrukturer som förser vårt samhälle med till exempel energi, vatten, livsmedel, transport, kommunikation, hälso- och sjukvård och säkerhet.

Eftersom det inte är önskvärt med storskaliga störningar i kritisk infrastruktur har många länder och organisationer upprättat riskhanteringsprogram och policyer, bland andra Sverige och Europeiska unionen. Dessa program och policyer innebär att man genomför risk- och sårbarhetsbedömningar för att identifiera potentiella händelser eller sårbara komponenter som kan orsaka störningar samt att uppskatta deras konsekvenser. Dock har flera studier visat att svenska risk- och sårbarhetsanalyser sällan tar hänsyn till kaskadeffekter. Därför är det av vikt att undersöka nuvarande praxis för att beakta kaskadeffekter och de potentiella utmaningar som svenska myndigheter och operatörer av kritisk infrastruktur står inför.

Det övergripande syftet med denna avhandling är att bidra med kunskap och metoder som kan användas för att stödja analyser av kaskadeffekter mellan ömsesidigt beroende kritisk infrastruktur. För att uppnå detta syfte har kaskadeffekter studerats med hjälp av olika metoder inom ramen för den svenska implementeringen av EU:s översvämningsdirektiv och CER-direktivet (Directive on the resilience of critical entities). Metoderna som används inkluderar en scoping-studie, dokumentanalys, analys av artikelsökord, workshops, intervjuer, sårbarhetsanalys, modellering och simulering.

Ett av de viktigaste resultaten är att svenska risk- och sårbarhetsanalyser brister i hänsyn till kaskadeffekter trots att inblandade aktörer är medvetna om deras betydelse. Dessutom behandlas kritiska infrastrukturer ofta som fristående system, vilket gör det svårt att identifiera kaskadeffekter. Införandet av kaskadeffekter i planerna för hantering av översvämningsrisker går långsamt. Avhandlingen identifierar också utmaningar för aktörerna när det gäller att bedöma kaskadeffekter i risk- och sårbarhetsanalyser. Det handlar bland annat om brist på genomförbara metoder för att analysera ömsesidiga beroenden, svårigheter att få tillgång till nödvändiga data, hantering av sekretess, begränsade resurser och begränsad tid samt oklara fördelar i förhållande till kostnader.

För att övervinna några av dessa utmaningar utvecklades, som en del av denna avhandling, en metod (AB-CEM) för att hjälpa riskanalytiker att identifiera och analysera ömsesidiga beroenden och kaskadeffekter. Metoden utformades för att

vara ett enklare men ändå vetenskapligt grundat alternativ för yrkesverksamma jämfört med de metoder som presenteras i vetenskaplig litteratur. Ett annat viktigt steg för att förbättra förutsättningarna för risk- och krishanterare att bedöma kaskadeffekter är att göra ett samordnat, nationellt initiativ för att samla in data om kritisk infrastruktur och ömsesidiga beroenden. För att sprida dessa uppgifter till relevanta intressenter är det också nödvändigt att inrätta säkra plattformar för delning av känsliga data om kritisk infrastruktur. Tydligare riktlinjer för hantering av konfidentiella eller sekretessbelagda uppgifter skulle dessutom vara till stöd för regionala experter som arbetar med översvämningsrisker och som arbetar med känsliga uppgifter. Ett bibliotek med dokumenterade redogörelser för kaskadeffekter skulle också kunna vara till hjälp för riskexperter.

Avhandlingen betonar vikten av att ta hänsyn till kaskadeffekter i bedömningar av resiliens för att säkerställa omfattande identifiering och minskning av potentiella risker och sårbarheter. Om kaskadeffekter ignoreras kan många potentiella samhällseffekter förbli oredovisade, särskilt för de mer extrema scenarierna. Att integrera kaskadeffekter mellan kritisk infrastruktur i resiliensbedömningar är därför avgörande för effektiv styrning och uppbyggnad av ett motståndskraftigt samhälle.

# Acknowledgements

I am grateful for all the support I have received during the years I have worked on this thesis. First, I would like to thank the Swedish Civil Contingencies Agency for funding the CenCIP project and the Swedish risk management system professionals for participating in my studies.

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To my family and friends, thank you for being there and reminding me that there are more important things than work. To my parents, Marjolein and Rikard, thank you for sharing your life wisdom and loving me no matter what. To my siblings, Malin, thank you for your PhD advice and endless, inspiring empathy; Joel, thank you for your wit and always having delicious meals ready whenever I visit; and Erik, thank you for the countless hours of games and play, both as kids and adults. To Opa Bob, thank you for inspiring my interest in engineering. To Phu, thank you for all the talks and adventures. A day with you is always a good one. To Chris, thank you for being a loyal friend and workout buddy. To Davo, Yaya, Scott, and Christina, thank you for all the board game nights, barbeques, and other fun times.

To my love, Lingping, for bringing a new level of brightness and joy into my life and supporting all my endeavours. You are everything I could have hoped for in a partner and more.

# List of Papers and Author's Contributions

Throughout this thesis, square brackets will refer to work that I have authored. Majuscule Roman numerals (i.e. [I]) refer to appended papers, and minuscule Roman numerals in square brackets (i.e. [i]) refer to related publications.

*Paper I*

**Arvidsson, B.**, Johansson, J., Guldåker, N. (2021). Critical infrastructure, geographical information science and risk governance: A systematic cross-field review. Reliability Engineering & System Safety, 213, 107741.

I was the primary author. Study conceptualisation together with my co-authors. I had a major role in data collection and analysis and a medium role in writing the manuscript and managing revisions.

*Paper II*

**Arvidsson, B.**, Guldåker, N., Johansson, J. (2022). A methodological approach for mapping and analysing cascading effects of flooding events. International Journal of River Basin Management, 1-13.

I was the primary author. Study conceptualisation and development of the method together with my co-authors. I had a medium role in writing the manuscript and managing revisions.

*Paper III*

**Arvidsson, B.**, Johansson, J. (2024). Flood risk assessments – exploring maturity and challenges in Sweden. Journal of Flood Risk Management, Pre-published online.

I was the primary author. I conceptualised the study with the co-author and was responsible for data collection and analysis. I also had a major role in writing the manuscript and managing revisions.

*Paper IV*

**Arvidsson, B.**, Johansson, J. (2024). Exploring the importance of cross-sector information for interdependent critical infrastructure governance. Manuscript.
I was the primary author. I conceptualised the study in discussion with the co-author and had a major role in coding and simulations. I also had a major role in writing the manuscript.

# Related publications

*Publication i*

**Arvidsson, B.**, Johansson, J., Hassel, H., Cedergren, A. (2015). Investigation method for cascading effects between critical infrastructures. The annual European Safety and Reliability Conference ESREL, September 7-10, 2015, Zürich.

The conference article presents an empirical method for gathering and structuring data information on cascading effects after a crisis. It was applied in the case of flooding in Malmö 2014. It was proven useful for identifying both cascading effects and conditions that can prevent or aggravate the consequences.

*Publication ii*

Johansson, J., Hassel, H., Cedergren, A., Svegrup, L., **Arvidsson, B.** (2015). Method for describing and analysing cascading effects in past events: Initial conclusions and findings. The annual European Safety and Reliability Conference ESREL, September 7-10, 2015, Zürich.

The conference article presents a method for describing and analysing cascading effects in past events. It was used to categorise cascading effects in 16 past large-scale events, including natural hazards, technical errors and terrorist attacks.

*Publication iii*

Johansson, J., Hassel, H., Petersen, K., **Arvidsson, B.** (2015). Metoder för konsekvensanalys på samhällsnivå [Methods for analysing consequences on a societal level]. Karlstad, Swedish Civil Contingencies Agency. Rapport number MSB906.

The purpose of this report was to provide a foundation for MSB to develop a method for analysing consequences at a societal, cross-sectorial level. This was achieved by reviewing the current state of risk- and vulnerability analyses (RVA:s) from 30 government authorities in Sweden and interviewing Dutch and US agencies responsible for critical infrastructure protection. One main conclusion is that it could be possible to analyse consequences on a societal level with a bottom-up approach, mirroring the Swedish crisis management system, if a system for collecting and disseminating critical infrastructure and interdependency data were developed.

*Publication iv*

**Arvidsson, B.** & Cedergren, A. (2016). Case Studies of Risk Governance – A Literature Review. The annual European Safety and Reliability Conference ESREL, September 25-29, 2016, Glasgow.

In this conference article, we reviewed the risk governance literature in search of case studies where risk governance principles have been applied. The case studies focus on designing institutional arrangements to meet new complex risks, particularly on centralisation versus decentralisation and the role of stakeholder participation. In addition, we found limited case studies related to critical infrastructure in the material.

*Publication v*

Johansson, J., **Arvidsson, B.** & Tehler, H. (2017). Kunskapsöversikt säkra flöden, försörjningssäkerhet och kritiska beroenden [Scientific review of critical supply flows, security of supply and critical dependencies]. Karlstad, Swedish Civil Contingencies Agency. Rapport number MSB1115.

A review of research related to critical infrastructure, supply chain risk management and security of supply on a societal level. The study was commissioned by MSB and focused on identifying research gaps in this area, particularly in the Swedish context. The study shows that the most developed research area is the security of supply, whereas critical infrastructure and interdependency areas are the least developed. The three investigated topics do not form a research area of their own; they can instead be considered a subset or specialised perspective of a diverse set of research disciplines with different conceptual, methodological, and contextual backgrounds.

*Publication vi*

Guldåker, N., Johansson, J., **Arvidsson, B.** & Svegrup, L. (2018). Utvecklad riskhantering för samhällsviktiga verksamheter avseende översvämningsrisker [Improved flood risk management for critical infrastructures]. Karlstad, Swedish Civil Contingencies Agency. Rapport number MSB1352.

The report provides an Area-Based Cascading Effect Method (AB-CEM) for collecting and organising data from critical infrastructure experts and analysing potential direct and indirect consequences. It is intended to support the County Administrative Boards (CABs) and their work with the Floods Directive. Incorporates a geographical information perspective. Additionally, the report provides examples for visualising indirect consequences. This report was the foundation for Paper II.

*Publication vii*

**Arvidsson, B.**, Johansson, J., Guldåker, N., Svegrup, L. (2018). Method for cascading effect analysis in flooding events. IAHR Europe Congress, June 12–14, 2018, Trento.

A two-page conference article that summarises the AB-CEM method [v] and plans for future development and testing. Based on publication vi.

*Publication viii*

Johansson, J., Guldåker, N., Hall, O., **Arvidsson, B.** & Erlström D. (2023) Data för identifiering av samhällsviktig verksamhet på nationell nivå vid extrem nederbörd och skyfall. [Data for identifying critical infrastructure on a national level related to extreme precipitation and cloud burst scenarios]. Karlstad, Swedish Civil Contingencies Agency. Rapport number MSB2343

The study reviews the current openly available databases, particularly geodatabases, that contain valuable information for identifying and analysing nationally relevant critical infrastructure and interdependencies. It focuses on risks relating to extreme precipitation and cloud burst scenarios, but it should also be useful for other hazards and threats. The study identified many pertinent datasets containing critical infrastructure data. However, in many sectors, the data is often limited to geolocations. To enable more advanced analyses, there is a need for more relevant CI attributes, such as flows, capacities, or interdependencies.

# Abbreviations

| | |
|---|---|
| AB-CEM | Area-Based Cascading Effect Method |
| CAB | County Administrative Board (Länsstyrelse) |
| CER | Directive (EU) 2022/2557 of the European Parliament and of the Council on the resilience of critical entities. |
| CI | Critical Infrastructure |
| CIR | Critical Infrastructure Resilience |
| ECI | Directive (EU) 2008/114/EC on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection. |
| EU | European Union |
| FD | Floods Directive – Directive (EU) 2007/60/EC of the European Parliament and of the Council on the assessment and management of flood risks. |
| GIS | Geographical Information System |
| GIScience | Geographical Information Science |
| MSB | Swedish Civil Contingency Agency (Myndigheten för Samhällsskydd och Beredskap) |
| RQ | Research Question |
| RVA | Risk- and Vulnerability Analysis |

# Introduction

Cascading effects are (negative) consequences that cannot be directly attributed to an initial failure, disruption, or disaster but result from complex interactions between critical social and technical systems in society (Pescaroli & Alexander, 2015). Understanding and accounting for cascading effects is essential for assessing the societal impacts of natural hazards (Gallina et al., 2016; Tang et al., 2019; Tsavdaroglou et al., 2018), climate change (Lawrence et al., 2020; J. Xu et al., 2009), supply chain disruptions (Ghadge et al., 2022; H. Li et al., 2017; Zhao et al., 2019), ecosystem disruptions (Buma, 2015; Rocha et al., 2018; Scheffer et al., 2005), or antagonistic attacks (K. Li et al., 2021; Palleti et al., 2021). In the past few decades, cascading effects have played a central role in some highly disruptive events (Johansson et al., 2015), for example, during Hurricane Sandy 2012 (Haraguchi & Kim, 2016), the 2007 floods in the UK (Pitt, 2008), the 2021 floods in Germany (Fekete & Sandholz, 2021), the 2003 blackout in the US and Canada (McDaniels et al., 2007), and the Eyjafjallajökull eruption in 2010 (Alexander, 2013).

One of the main reasons for cascading effects is the interdependent nature of Critical Infrastructures (CIs) (Haimes, 2009; McDaniels et al., 2007; Pescaroli & Alexander, 2015; Rinaldi et al., 2001) that supply our society with for example, energy, water, food, transportation, communication, healthcare, and security. At first glance, it may seem like CIs and their organisations are stand-alone systems, where the power system delivers electricity, fibreoptic cables deliver electronic data, etc. However, delving further into the systems' functionality reveals an intricate web of interdependencies. For example, modern CIs almost ubiquitously depend on electricity and telecommunication systems. One of the main challenges with assessing cascading effects is identifying, mapping, and understanding these interdependencies. However, the current trend is that CIs are becoming increasingly interconnected, mainly through digitalisation and electrification, which has played an essential role in increasing efficiency but has also created more dependencies (OECD, 2011, 2019). A second trend is institutional fragmentation and division of responsibility in CIs, driven by liberalisation, privatisation, deregulation, and outsourcing (De Bruijne et al., 2006; De Bruijne & Van Eeten, 2007). This, in turn, brings additional complexity when assessing cascading effects by requiring the involvement of more and more stakeholders. Therefore, viewing CIs as a system-of-systems rather than a collection of stand-alone systems is becoming increasingly crucial. This is one of the aims of critical infrastructure (CI) research, which is concerned with the safe and reliable operations of CIs (Alcaraz & Zeadally, 2015; Zio, 2009). In the recent decade, this research field has moved from a protection perspective towards a broader resilience perspective, also emphasising, for example, recovery from incidents and adaptation to new circumstances; as such, it is often referred to as critical infrastructure resilience (CIR).

CIs are owned, operated, and managed by both public and private entities, and it is desirable to minimise disruptions from both a societal and a business point of view. For society, disruptions in CIs can negatively impact the health and safety of citizens, economic activity, or the environment (European Commission, 2022b). For businesses, disruptions are often costly in terms of repairs or lost profits and can cause reputational damages (Ludvigsen & Klæboe, 2014). A common approach is to conduct risk and vulnerability assessments to identify potential events or vulnerable components that could cause disruptions and estimate their possible consequences. From a societal point of view, there are several programmes and policies in the European Union (EU) and Sweden that mandate risk assessments, for example, the EU Floods Directive (European Commission, 2007), the EU CER Directive (European Commission, 2022b), or the Swedish Risk and Vulnerability regulations (SFS 2006:544). Ideally, these assessments should include cascading effects, but suitable methods, data, and resources are needed to achieve this. Since analyses of cascading effects typically involve several organisations, structures and incentives for cooperation also need to be in place. However, several studies have shown that Swedish risk and vulnerability assessments rarely consider cascading effects (Johansson, Hassel, Petersen, et al., 2015; Norén et al., 2016). Ignoring cascading effects means that consequences often are underestimated, which may result in a false sense of security and inadequate resource allocation for mitigating societal risks. This warrants an investigation into the current practices of considering cascading effects and the potential challenges Swedish governmental agencies and CI operators face.

The overall research aim of this thesis is to contribute knowledge and methods that can be used to support analyses of cascading effects across interdependent CIs. More specifically, the goal is for the knowledge to help risk analysts more significantly consider cascading effects in Swedish risk assessments.

## Research process and research questions

As a master's student in 2014 and 2015, I was involved in an EU-FP7 project abbreviated CascEff, which focused on understanding and managing cascading effects in large-scale crises such as the European blackout in 2006, Hurricane Sandy in 2012, and the Eyjafjallagökull eruption in 2010. As a part of the research team, I developed a framework that defined cascading effects (Johansson et al., 2015), set out an empirical method (Arvidsson, 2015), and identified and mapped cascading effects in past crises (Johansson et al., 2015). I noticed that many incident reports and investigations following these crises focused heavily on the aspects leading up to the crisis but made little effort to investigate the following consequences, specifically cascading effects (Arvidsson, 2015).

Another influence on the direction of this thesis was my affiliation with the Lund University Centre for Critical Infrastructure Protection Research (CenCIP). The purpose of CenCIP is to contribute to developing a more resilient society through research and education. Some of the centre's primary goals are to study interdependencies between CIs and disruptions they may cause, develop methods for analysing CIs, and study how CI resilience can be achieved.

The research in this thesis focuses on the assessment of cascading effects between CIs and can be summarised in the following research questions:

> **RQ 1:** How are cascading effects between CIs identified and assessed in Sweden?
>
> **RQ 2:** What challenges do actors face when assessing cascading effects in a CI context?
>
> **RQ 3:** How can the assessment of cascading effects between CIs be improved, better incentivised, and more utilised?

The research journey started with a focus on how to improve assessments of cascading effects from a more theoretical perspective (RQ 3), resulting in Paper I. I then got the opportunity to investigate current practices and challenges related to assessing cascading effects from a more practical perspective (RQ 1 & 2) through commissioned work with the Swedish Civil Contingencies Agency (MSB) in Papers II and III. In Paper IV, I returned to a more theoretical focus on improving assessments and the limitations of current assessment practices for governing CIs (RQ 3). The order of the research questions in this thesis is in line with the logical order of the results and discussions, and thus, it does not follow the chronological order of the appended papers. A schematic overview of the relationships between the research questions and publications is presented in Figure 1. The following sections provide more details of the research process related to each question.

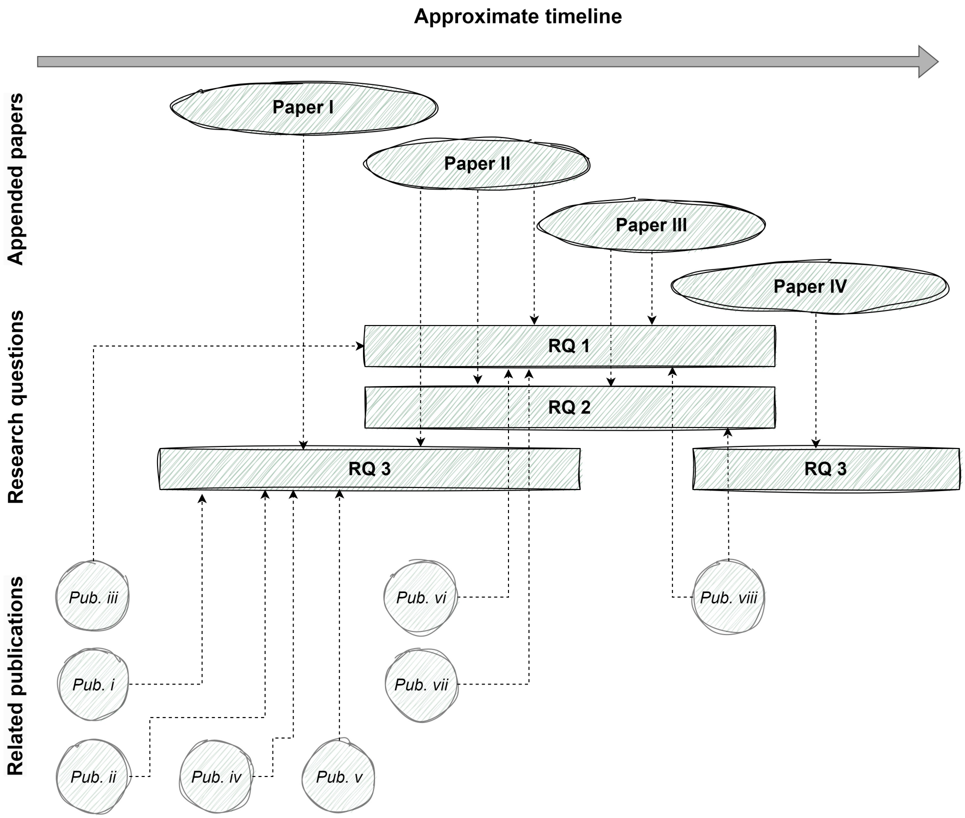


**Figure 1.** A schematic overview of the relationship between the research questions (RQ), the appended papers and the related publications.

The first research question focused on understanding cascading effects in the Swedish context and was explored in both Papers II and III and Publication ii, vi, vii, and viii. In Paper II, my co-authors and I studied the inclusion of CI in flood risk management plans as part of the Floods Directive. Here, we gained substantial practical insights through several workshops with local and regional risk managers, CI operators and MSB. Several flood risk management plans and regulatory documents were also read in the study to provide further insights. In Paper III, the main tangible products of the FD, i.e., flood risk management plans and flood risk assessments, were studied systematically using qualitative content analysis and assessing the maturity of the assessments. Additionally, interviews with County Administrative Boards gave more profound insights into their processes and the challenges they encounter.

The research process for the second research question was highly intertwined with the first since talking to the actors involved in the FD about assessing cascading effects inevitably involved discussing challenges they face. Thus, some challenges were revealed in the workshops of Paper II. However, the interviews with CABs in Paper III explicitly focused on answering this question, leading to more in-depth insights. Further, having a more thorough understanding of the relevant assessment processes and the main challenges helped design the study in Paper IV.

One way to approach the third research question is to look at related research fields for inspiration. Thus, in Paper I, we looked beyond the CI field to find potential ways to address two key challenges for CIR: interdependencies (and cascading effects) and the multi-actor setting. More specifically, opportunities and challenges for interdisciplinary research were investigated through a scoping review of three research fields: 1) Critical infrastructure, 2) Risk Governance and 3) GIScience. One finding in the paper was that flood risk management seems to be an area of research with good opportunities for studying critical infrastructure and cascading effects. Another opportunity was integrating GIS data and tools methods and tools related to CIR. Initially, the intent was to do more research related to GIScience and RG. However, around the time of Paper I, the commissioned study directed me towards flood risk management.

Another way to approach the third research question is to develop new methods or approaches for assessing cascading effects, which was the focus of Paper II. From talking to and interviewing flood risk managers at municipal and regional governments, it became clear that they knew the perils of cascading effects but lacked practical methods and data. This inspired my co-authors and me to develop a scientifically based and practical method to map and structure data relevant for analysing cascading effects between critical infrastructures, partly based on the findings in Paper I. The method was named the Area-Based Cascading Effect Method (AB-CEM).

A third way to address the third research question is to directly study the challenges of assessing cascading effects. Data availability and confidentiality were consistently identified as challenges for various actors, such as county administrative boards, municipalities, and CI operators. Paper II addressed the availability challenge by providing a method for mapping essential data. However, the data confidentiality challenge remained. Risk management and governance literature often claim that information sharing is vital for managing risk in complex systems such as CI but provides little practical guidance. The new EU CER directive also suggests setting up infrastructure for sharing CE data, including interdependencies (European Commission, 2022b). Such information is fundamental for a CI operator's ability to consider interdependencies in their analyses and for public crisis management actors' ability to perform analyses on a system-of-system level. In Paper IV, we use a modelling and simulation approach to gain insights into how the availability or restriction of interdependency information affects each CI's ability to perform vulnerability analysis and how their assessment of critical scenarios would compare to a system-of-system level analysis. The simulation allowed us to test two fundamental approaches currently used for addressing the issue of cascading effects in CI: internalising consequences and continuity management. The results revealed some limitations of how cascading effects are assessed today, which has implications for CI governance.

## Ethical considerations

One of the subjects of this thesis is the resilience of critical infrastructures, which impact society. In one part of the thesis, I analyse the vulnerability of CIs, which can help gain insights into how to improve their resilience. However, publishing real CI vulnerability analysis is also dangerous, as it can just as easily be exploited for nefarious purposes, making it a threat to CIs. Therefore, the study uses realistic but not too accurate or current data to consider the potential security implications.

The thesis also includes data from interviews, which also require some considerations. First, the respondents received the questions in advance and were informed that the interviews would be used for research purposes so that they could consider that before agreeing to an interview. Second, their names have been kept anonymous to avoid any potential repercussions. Third, the respondents had the opportunity to review the transcripts to ensure that they contained no sensitive information and were not misrepresented.

# Background

## Critical Infrastructure

One of the first uses of the term *critical infrastructure* is attributed to President Bill Clinton's Commission on Critical Infrastructure Protection in 1996, in which the concept of critical infrastructure was coined as:

> 'essential to the defence and economic security of the United States, the smooth functioning of government at all levels, and society as a whole' (Moteff & Parfomak, 2004, pp. 3–4)

Since then, many countries and other international bodies have initiated CI policies, action plans or programs. In certain countries or contexts, the terms *lifeline systems*, *utilities*, *vital societal functions*, or *critical entities* are used and can be considered closely related concepts (European Commission, 2022b; McDaniels et al., 2007; Pursiainen, 2018; Pursiainen & Kytömaa, 2023). Because there are different contexts, traditions and values across countries, there is no real international consensus, neither political nor academic, on which societal systems should be considered critical infrastructures. There are, however, many similarities where systems for telecommunication, electricity, health care, gas and oil, transportation, banking and finance, water supply, emergency services and continuity of government are typically considered critical infrastructures (European Commission, 2022b; Moteff & Parfomak, 2004; MSB, 2023).

At the start, there was a focus on *protection.* However, during the last decade, there has been a shift towards *resilience* in policy and research, moving from a mindset of protection from antagonistic threats towards a broader concept that includes the reliability, vulnerability, safety and recovery of critical infrastructures (Pursiainen & Kytömaa, 2023). One example is the name change in the EU programs from the 'Directive on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection' (or the ECI directive) to the 'Directive on the Resilience of Critical Entities' (or the CER directive or CER) in 2022. Critical entity is a concept introduced with the new directive and defined as 'providers of essential services' (European Commission, 2022b, §1). For this thesis, critical entities can be equated with critical infrastructure operators. To align with the new EU and Swedish nomenclature, I use Critical Infrastructure Resilience (CIR) as the overarching concept in this thesis.

The European Union directives, like CER, play a significant role in Sweden's CIR efforts, providing a common framework for CIR-related work across the EU. Furthermore, the former ECI and the new CER aim to enhance cooperation and information sharing between Member States and between public and private sector stakeholders to improve the resilience of critical infrastructure within the EU. In addition to these directives, sector-specific regulations impose similar or stricter rules, especially in the energy and IT sectors (European Commission, 2022a; European Parliament, 2019). MSB primarily coordinates critical infrastructure protection in Sweden. However, many sector-specific regulations are issued by their respective oversight agencies, such as the Swedish Energy Agency, Swedish Transport Administration, or Swedish Post and Telecom Authority.

There are several identified challenges related to CER. The first is the complexity of CI systems and the interdependencies between them (Haimes, 2009; OECD, 2019; Rinaldi et al., 2001), which makes it difficult to predict their behaviour and subsequently assess risk and vulnerability (Alcaraz & Zeadally, 2015; Zio, 2009). This challenge was also one of the reasons for replacing the ECI directive with the CER directive since the evaluation of ECI found that it did not adequately address CI interdependencies (European Commission, 2020). For example, the ICT and space sectors have become increasingly important, contributing to increased interdependencies between CIs (European Commission, 2020).

A second challenge is institutional fragmentation and division of responsibility, driven by liberalisation, privatisation, deregulation and outsourcing (De Bruijne et al., 2006; De Bruijne & Van Eeten, 2007). A few examples from Sweden are the deregulation of railways, completed in 2012 (Alexandersson & Rigas, 2013), and the liberalisation of the telecom sector, postal services, the electricity market and domestic flights since the 1990s (Statskontoret, 2004). For example, the increased number of actors has led to an increased difficulty in administrating systematically collected and accessible data relevant to understanding complex systems and interdependencies (OECD, 2011). It has also introduced competition between CI operators, which incentivises a focus on gaining market shares rather than ensuring reliable services (Cedergren et al., 2019; De Bruijne & Van Eeten, 2007).

A third challenge is information security and confidentiality concerns, potentially creating a reluctance to share information between CI operators and between CI operators and public authorities (Brem, 2015). This challenge has also been magnified by institutional fragmentation, as more actors need to cooperate and share information to manage their resilience effectively.

Assessing cascading effects can be challenging because critical infrastructure (CI) is complex on a system-of-system level, making the process cumbersome. Additionally, institutional fragmentation and confidentiality can hinder cooperation and information sharing between institutions, adding to the difficulty of identifying critical interdependencies and better understanding CIs.

One context in which it is essential to consider cascading effects is flood risk management since flooding can cause significant damage to buildings, roads, railways, bridges, and other critical infrastructures. The following section provides some background to this context from a Swedish perspective.

## Floods Directive in Sweden

In Europe, the primary driver of flood risk management is the *EU directive on the assessment and management of flood risks* (or the Floods Directive or FD) (European Commission, 2007). It was issued in response to several severe floods in the EU, particularly the Central European floods in 2002 in the Danube and Elbe river systems (Ulbrich et al., 2003). The directive aims to reduce the societal impacts of flood events by establishing a mandatory flood risk management framework for member states. The FD establishes a six-year cycle with the following steps: conducting a national overview of flood-prone areas (Step 1), creating flood hazard maps for these areas (Step 2a), generating flood risk maps (Step 2b), and developing flood risk management plans (Step 3), see Figure 2.

In Sweden, the overall responsibility for implementing the FD is assigned to MSB, which is also mandated to issue regulations (SFS 2009:956). MSB also manages the funding related to the FD, for example, for flood risk reduction measures. However, MSB is supported by County Administrative Boards (CABs). Out of the steps in the FD cycle (see Figure 2), MSB is primarily responsible for steps 1 and 2a, while the CABs are primarily responsible for steps 2b and 3.

MSB provides general flood hazard maps for all major rivers and lakes in Sweden and coastal flood risk assessments. Each CAB then uses the national overview and flood hazard maps to construct flood risk maps within their jurisdiction and proposes appropriate measures through flood risk management plans. These plans are communicated to municipalities, landowners, critical infrastructure operators, citizens and other stakeholders. However, CABs lack the authority to enforce any measures; as such, it is up to each stakeholder to implement their desired measures (SFS 2009:956).

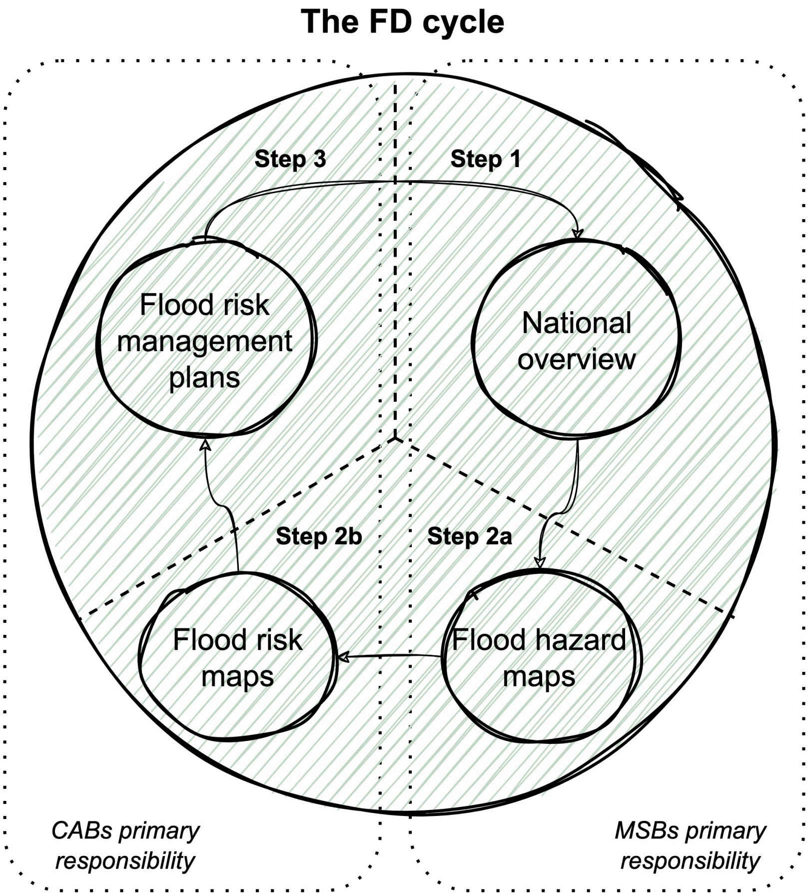


**Figure 2.** Overview of the FD cycle and division of responsibilities in Sweden.

The implementation of the FD has been studied in several Member States. Priest et al. (2016) reviewed the implementation of the first FD cycle in six member states and concluded that member states can pass the requirement with relatively low effort. Another identified issue with the FD is that it does not provide any guidance on which metrics should be used to measure flood risk, for example, whether individual or societal risk measures should be considered (Mostert & Junier, 2009).

Related to this thesis, one of the identified challenges with the FD is the lack of a coherent approach for considering cascading effects among EU Member States (Nones & Pescaroli, 2016). It has also been found that there are significant differences in the data structures and flood risk assessment formats between Member States (Müller, 2013; Nones, 2015).

# Key concepts

This chapter briefly describes the fundamental concepts used in the thesis and their relation to CI. First, interdependencies, cascading effects, and related concepts will be described. The second section deals with how resilience, risk, and vulnerability relate to each other. The third section presents the risk governance framework and its main principles. Lastly, GIS and GIScience are introduced briefly.

## Interdependencies and Cascading Effects

In a CI context, a dependency can be defined as:

> ‘A linkage or connection between two infrastructures, through which the state of one infrastructure influences or is correlated to the state of the other’ (Rinaldi et al., 2001, p. 14).

The terms dependency and interdependency are often used interchangeably. However, there is sometimes a need to differentiate between them. In this thesis, a dependency refers to a one-way relation between systems (left in Figure 3). In contrast, an interdependency refers to a two-way relation between systems, either directly (left in Figure 3) or indirectly through a feedback loop (right in Figure 3) (Johansson & Hassel, 2010; Rinaldi et al., 2001; Setola & Theocharidou, 2016).

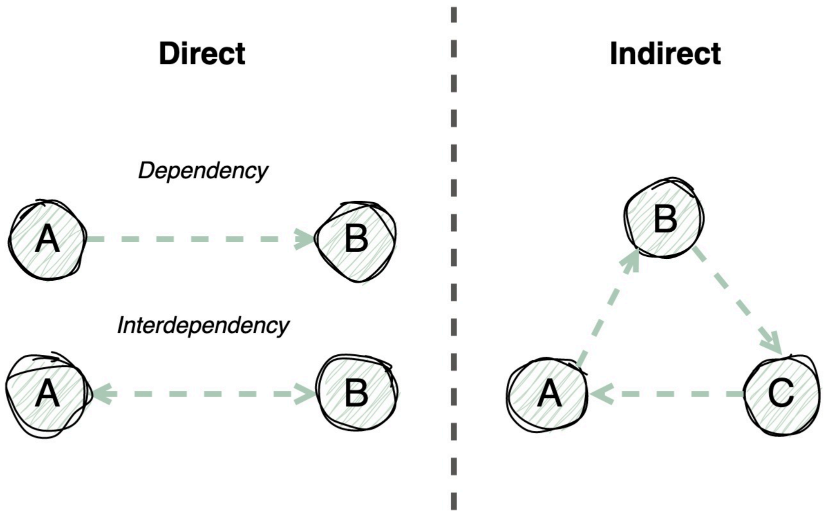


**Figure 3.** Illustration of dependency and interdependency and direct and indirect interdependencies.

Dependencies can also be classified based on the kind of connection that exists between two infrastructures (Rinaldi et al., 2001), where a:

- Physical (inter)dependency refers to when an infrastructure's operations depend on a physical output from another (e.g., power or water).
- Cyber (inter)dependency refers to when an infrastructure's state depends on information transmitted through the information infrastructure.
- Geographical (inter)dependency refers to when elements of multiple infrastructures are in close spatial proximity.
- Logical (inter)dependency refers to when the state of one depends on the state of the other via control, regulation, or other mechanisms that cannot be considered physical, geographical, or cyber.

Interdependencies between infrastructures can lead to consequences that spread from one system to another. Depending on the context, these consequences are often called indirect or cascading effects. For instance, indirect consequence is a well-established concept in flood risk management (Jha et al., 2012; Klijn et al., 2009; Merz et al., 2010; Schumann, 2011), while cascading effects are more commonly used in CI contexts (Hilly et al., 2018; Johansson et al., 2015; Nones & Pescaroli, 2016; Rinaldi et al., 2001). This thesis considers the concepts synonymous, but the term 'cascading effect' is preferred, as it is more closely related to CI and better captures that it is a dynamic phenomenon. However, both terms have been used in the appended papers. For example, indirect consequence was used in papers related to flood risk management.

Since one cascading effect can lead to another, it is sometimes necessary to specify the order in which they occur. For example, if an initiating event, such as a natural hazard, failure or disruption, happens and impacts System A, this is considered the direct effect (Johansson et al., 2015). If the impact on System A leads to an impact on System B, this is regarded as a first-order cascading effect, and so on (see Figure 4).

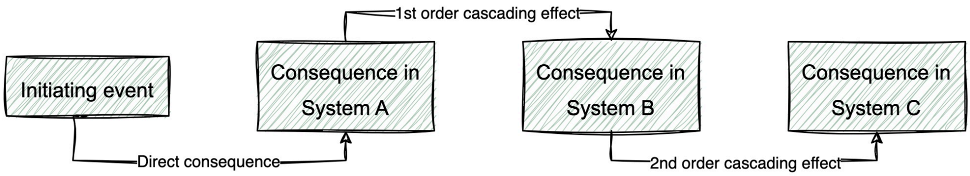


**Figure 4.** Schematic overview of orders of cascading effects. It is adapted from [ii].

CI and risk management literature use three principally different meanings of cascading effects. First, a cascading effect can refer to an event where an infrastructure (negatively) influences another infrastructure. Secondly, cascading effects can refer to when conditions within an infrastructure trigger more or larger consequences within the same infrastructure, sometimes also called cascading failures. This occurred, for example, in the 2003 blackout in the United States and Canada, where a failure in a high-voltage power line led to the overloading of additional power lines, which consequently caused more lines to fail until much of southeast Canada and eight states in the US were affected by the blackout (OECD, 2019; U.S.-Canada Power System Outage Task Force, 2004). Thirdly, cascading effects can refer to when a natural hazard triggers additional hazards. For example, a flood can lead to ground instabilities and cause a landslide (Gill & Malamud, 2014). In this thesis, I focus on the first kind of cascading effects, where an infrastructure negatively influences another infrastructure and subsequently impacts society.

Three main approaches exist to identify and analyse interdependencies and cascading effects between CIs. One approach is to consult CI experts and ask them to estimate the strength of interdependencies or consequences of cascading effects. This can, for example, be done through surveys (Laugé et al., 2015; Moon et al., 2015; Toubin et al., 2012), interviews (Chang et al., 2014), or workshops (Chang et al., 2014; de Bruijn et al., 2016; Deltares, 2023; Moon et al., 2015). These methods mainly identify interdependencies and gather data for further analysis. The second approach is to look at past events that led to cascading effects between CI to gather empirical evidence and draw conclusions about the prevalence or nature of interdependencies (Johansson et al., 2015; E. Luiijf & Klaver, 2021; H. A. M. Luiijf et al., 2010; McDaniels et al., 2007). Lastly, simulation-based approaches use models of CIs and their interdependencies to study how cascading effects arise. This approach is generally quite demanding and requires expertise in, for example, engineering, mathematics and computer science. The success of such an approach is also highly dependent on available and accessible CI and interdependency data. However, it might also be the most powerful approach for studying cascading effects since it allows for experimentation with systems which would otherwise be too costly, dangerous, disruptive or morally objectionable (Birta & Arbez, 2007 Ch. 1.). Using the simulation-based approach can help reveal bottlenecks or vulnerabilities in the system that would not be possible otherwise (Pursiainen & Kytömaa, 2023). Several relevant kinds of models can be used to model CIs, such as agent-based models (Dudenhoeffer et al., 2006; Ehlen & Scholand, 2005; Kaegi et al., 2009), system-dynamic models (Brown et al., 2004; Min et al., 2007), graph-based models (Espada et al., 2015; Hines et al., 2010; Johansson et al., 2011; Lee II et al., 2007; Viavattene et al., 2015; Zio & Sansavini, 2011), national economic models (Barker & Santos, 2010; Haimes et al., 2005; Kelly et al., 2016; Svegrup et al., 2019; W. Xu et al., 2012) and flow-based models (Johansson et al., 2017; Svegrup et al., 2017).

# Resilience, Risk, and Vulnerability

Since the concepts of resilience, risk and vulnerability are used in many different domains, several definitions are available. There are constant efforts to create more unified definitions, but it has not proven easy. For example, the Society for Risk Analysis' attempts ended up with seven accepted definitions of risk (Aven et al., 2018). There are also published works on various definitions of resilience (Mentges et al., 2023) and vulnerability (Wisner, 2016).

Managing risk and vulnerability and building resilience are strategies to address uncertain and unwanted events in systems or society. A key difference lies in the kind of unwanted events they target: a risk-based approach tends to focus on events that are known and follow familiar patterns (Mentges et al., 2023), a vulnerability-based approach tends to focus on identifying system weaknesses, and a resilience-based approach tends to focus on a system's ability to respond to any event, even unexpected or unknown ones (Mentges et al., 2023). Thus, while risk management strategies traditionally focus on preventing hazards and avoiding exposure, vulnerability management focuses on reducing weaknesses, and resilience focuses on building robust systems that can absorb unexpected shocks, restore, and adapt to new circumstances. It should be noted that these concepts often intertwine; for example, risk or vulnerability assessments are ways to achieve a resilient system, and risk management can also include a more holistic approach, which includes improving a system's ability to respond to events.

There are two common interpretations of vulnerability in a CI context. The first interpretation comes from a risk perspective, where vulnerability is considered a contributor to risk, together with the hazard and the exposure to the hazard (Aven et al., 2018; Wisner, 2016). For this interpretation, a vulnerability must always be in relation to something, e.g., a particular event or hazard. For example, a system or society can have a high vulnerability to flood hazards but a low vulnerability to earthquakes. This interpretation is commonly used for risk assessments of natural hazards (Cutter et al., 2003; Espada et al., 2015; Tamaro et al., 2018). In the second interpretation, vulnerability describes a flaw or weakness in the design or management of a system that renders it susceptible to destruction or incapacitation regardless of the type of hazard or failure (Johansson et al., 2013; Zio, 2016). This thesis focuses exclusively on the second perspective on vulnerability.

Resilience is a concept used in many disciplines, such as ecology, economy and engineering (Mentges et al., 2023). There are several accepted definitions of resilience, but a core ability of a resilient system is to sustain and restore its basic functionality following a disruptive event (Aven et al., 2018; Mentges et al., 2023). Although resilience is a concept that encompasses many aspects, risk and vulnerability analyses still have a central role in analysing resilience (Zio, 2016). Since CI is the context of this thesis, resilience is defined as the ability of CIs to sustain and restore their basic functionality following a disruption.

## Risk Governance

This thesis adopts the definition of risk governance from the IRGC's white paper on Risk Governance (IRGC, 2006) as ‘the totality of actors, rules, conventions, processes, and mechanisms concerned with how relevant risk information is collected, analysed, and communicated, and management decisions are taken’ (IRGC, 2006, p. 22). The definition is valuable for critical infrastructure research, providing a lens to conceptualise and address the complexity, ambiguity, and uncertainty of risks and dependencies of critical infrastructures.

Risk governance is focused on managing systemic risks, which are complex, uncertain, and prone to cascading effects (IRGC, 2018). The framework addresses challenges like those seen in the 2008 global financial crisis or climate change (IRGC, 2018). Risk Governance aims to extend beyond conventional risk assessment and management, emphasising collaborative decision-making among diverse stakeholders with varying goals and perspectives (IRGC, 2006). It integrates factual dimensions, such as physical outcomes and probabilities, and socio-cultural dimensions, including living conditions, values, and emotions (IRGC, 2006).

The Risk Governance framework articulates three fundamental principles: the communication and inclusion principle, the integration principle, and the reflection principle (van Asselt & Renn, 2011). The communication and inclusion principle advocates involving a broad spectrum of stakeholders in decision processes related to systemic risks, with inclusivity proportional to risk complexity (van Asselt & Renn, 2011). This principle aims to identify and include diverse perspectives, incorporate information sources, and enhance democratic decision-making for socially robust outcomes (van Asselt & Renn, 2011). The integration principle underscores the need to integrate knowledge from various disciplines or sources (van Asselt & Renn, 2011). The reflection principle promotes collective reflection on uncertainties, complexity, and ambiguity, discouraging simplistic approaches to addressing risks (van Asselt & Renn, 2011). Positive outcomes associated with effective risk governance encompass clearly defined accountabilities, fairness, and transparency (Andersen et al., 2014; Dubreuil et al., 2002; European Commission, 2001; Renn & Schweizer, 2009).

# GIScience

Geographical Information Systems (GIS) originated in the '60s and '70s, gaining widespread use in academia and society during the '80s and '90s (Longley, 2011). GIS involves capturing, storing, manipulating, analysing, managing, and visualising geographic information (Harrie, 2020). A GIS typically comprises hardware, software, databases, procedures, and skilled personnel (Harrie, 2020). GIS-related research later became recognised as a distinct science, leading to the introduction of Geographical Information Science (GIScience) in the 1990s (Longley, 2011).

GIScience encompasses geographical data collection, spatial statistics, data modelling, spatial theories, data structures, algorithms, display, analytical tools, and considerations of institutional, managerial, and ethical issues (Goodchild, 2010). It is a multidisciplinary and multi-paradigmatic field, overlapping with computer science, statistics, mathematics, social science, and psychology (Mark, 2000, 2003). While closely tied to geography, some argue that GIScience is better considered a branch of information science, emphasising ontology, representation, and computational issues rather than explaining geographic phenomena (Mark, 2003).

In relation to critical infrastructure resilience, in this thesis, I view GIS as a valuable tool for data collection, modelling, and statistical analyses and GIScience as a broader discipline that can be used to theorise and conceptualise issues arising from GIS applications in various contexts, including critical infrastructure (Fekete et al., 2017; Longley, 2011).

# Methodology

Four studies were designed to address the research questions posed in this thesis. Each study is represented by one paper, which is sometimes supported by related publications. The diverse and interdisciplinary nature of the research field relating to CIR is reflected in the choice of study designs and methods that stem from social science and engineering traditions. Since each paper largely used separate methods, the methodology sections are structured paper by paper.

Table 1 summarises the study designs, methods, and materials used for the appended papers. The following sections describe each paper, related methods, and how the methods have been applied.

**Table 1. Study design, methods and material.**
An overview of the designs, methods and material used in the appended papers.

| Paper | Study design | Methods | Material |
|---|---|---|---|
| I | Literature review | Scoping study | Based on 51 681 identified articles, 268 reviewed abstracts, 105 fully read articles, and 51 selected articles. |
| | | Article keyword analysis | 14 170 articles. |
| | | Qualitative content analysis | 51 coded articles. |
| II | Design science | Workshop | Four workshops with local and regional flood risk managers, critical infrastructure operators and MSB. |
| III | Case study | Qualitative content analysis | 43 flood risk management plans and 55 flood hazard reports. |
| | | Interviews | 15 respondents from county administrative boards and government agencies in Sweden. |
| IV | Simulated Experiment | Modelling and simulation | A dataset on real-life power, ICT, and railway infrastructure, which includes supply, demand, and origin-destination data for 816 nodes and links. |
| | | Vulnerability analysis | Up to 4 simultaneous failures in the modelled systems. |

# Paper I – Scoping study of three research fields

The first paper was designed as a scoping study to review three research fields and compare approaches to addressing interdependencies and governance in CI. The choice of review method fell on the scoping study (Arksey & O'Malley, 2005) due to its suitability for mapping key concepts of research areas. To help identify and select relevant literature, we developed and applied a novel article keyword analysis. Finally, to map concepts and identify themes, the articles were analysed using a conventional qualitative content analysis (Hsieh & Shannon, 2005).

The primary purpose of a scoping study is to rapidly map key concepts of a research area (Arksey & O'Malley, 2005). The focus is on including a broad spectrum of articles and the article's relevance to the research question rather than on the depth and quality of the articles. This contrasts a scoping study from other literature review methods such as systematic reviews or meta-analyses (Poth & Ross, 2009). At the same time, a scoping study is more systematic than a narrative or literature review and requires a form of analytical interpretation of the literature (Levac et al., 2010). A scoping study consists of five key steps, presented in Figure 5. Arksey and O'Malley (2005) give four reasons to conduct a scoping study: 1) to determine the value of undertaking a full systematic review, 2) to examine the extent, range, and nature of research activity, 3) to summarise and disseminate research findings, 4) to identify research gaps in the existing literature. In Paper I, the scoping study was conducted for reasons 2, 3 and 4.

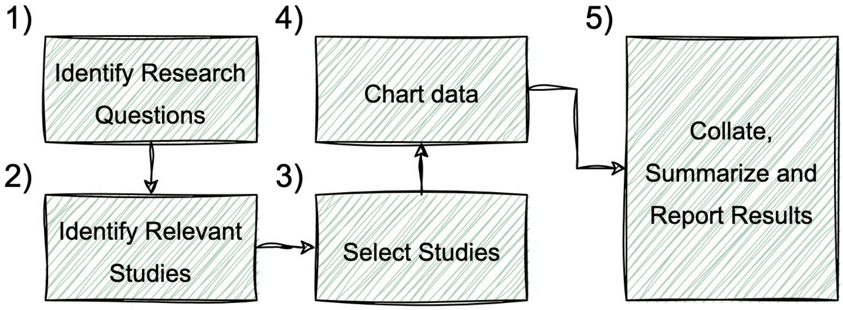


**Figure 5**. Overview of the five key steps in a scoping study according to Arksey and O'Malley (2005).

## Article keyword analysis

The article keyword analysis aimed to provide a broad overview of individual research fields, enable a comparison between research fields, identify articles central to one or more research fields, and support a content analysis. My co-authors and I developed the method presented in Paper I.

The first step of the keyword analysis is to rank the keywords in the reviewed literature based on their frequency. In this step, it is also recommended to cluster similarly spelt keywords and exclude generic keywords, such as geographical names (unless that is key to the review). The second step involves cross-referencing keywords from one field with other fields to identify keywords that overlap several fields or are unique to one. The third step is to calculate an Article Score using the rankings from step one. The article score is designed so that if an article uses keywords that are highly ranked in, for example, the CI field, it will receive a high score for that field. This scoring is repeated for each research field. For more details on the Article score, see Paper I.

In Paper I, the article keyword analysis was used to identify relevant articles for review. It was applied to 14 170 articles from the CI (3290), RG (880) and GIScience fields (10,000). The GIScience search initially yielded 47,511 articles, but to make the analysis more feasible, the amount of GIScience articles was restricted to the 10,000 most recently published articles at the time. The list of most frequent keywords was used to produce the coding schema used in the qualitative content analysis (see next section).

## Qualitative content analysis

Qualitative content analysis is a flexible research method for analysing text data to answer a research question (Hsieh & Shannon, 2005; White & Marsh, 2006). It aims to go beyond counting words to examine language and instead classify large amounts of texts into a more manageable number of categories that represent similar meanings (Weber, 1990). The analysis typically involves coding text with similar meaning and identifying common themes or patterns in the text (Hsieh & Shannon, 2005).

Hsieh and Shannon (2005) describe three different approaches to content analysis: the conventional, directed, and summative approaches. In a conventional approach, the aim is to gain a deeper understanding of an observed phenomenon. To achieve this, the initial codes are developed and refined during the data analysis and are based on the content sample. A directed approach instead aims to refine, verify, or expand on existing theories or research findings. The initial codes are based on the studied theory, and consequently, the codes need to be established before the data analysis. A summative approach examines the context or pattern in which particular words or phrases are used. In this approach, the initial codes originate from the researchers' interests and can be identified before and during data analysis.

Paper I aimed to structure and synthesise the scientific literature on research that overlaps three different research areas. The coding scheme was informed by keywords prevalent in all three fields and consisted of 46 codes divided into five categories (threats and hazards, concepts, methods, perspectives, and critical infrastructure sectors). Hence, the conventional approach was used in Paper I. The content of 51 articles was coded and organised using this method. The coding was applied on an article level, as opposed to, for example, paragraph or sentence level, meaning nuance is lost. However, this level was deemed sufficient for the study. Each article could have up to three codes per category, which was particularly important for mapping critical infrastructure sectors.

Qualitative content analysis is inherently a subjective endeavour (Weber, 1990), and it can be challenging to ensure the validity and reliability of the results (Long & Johnson, 2000). In Paper I, the article keyword analysis helped reduce bias in the selection process for cross-field articles by using a relatively neutral metric to select the most relevant articles. In cases where the coders were uncertain, all authors had to reach an agreement, which also helped to ensure the reliability of the results.

# Paper II – Designing a method (AB-CEM)

Paper II aimed to develop a method (AB-CEM) for mapping and analysing interdependencies and cascading effects in risk assessments. It was mainly developed for flood risk assessments, but a secondary aim was that it should apply to other hazards. Method development is one of the typical activities of design science research (Hevner et al., 2004). The study, therefore, follows the suggested design research activities from Carlsson et al. (2011), which were slightly adapted to fit the context: (1) formulate the design problem and desired outcomes, (2) review existing methods and practical work, (3) propose and refine the method, and (4) incremental testing of the method.

The problem was formulated in constructive dialogue with the Swedish authority MSB. Existing methods and approaches related to critical infrastructure, geographical information systems and flood risk assessment were reviewed to propose an initial design. The incremental testing of the AB-CEM feasibility took place during workshops with local and regional flood risk managers and CI operators. This was an essential part of the study as gathering feedback from potential users of the method provided valuable insights. Finally, AB-CEM was tested, through the supervision of the authors of Paper II, in an authentic setting through a master's thesis (E. Andersson & Carlström, 2020) that applied the method to a drought and a flood scenario in Karlshamn municipality, where they engaged with local CI operators from the municipal and private sectors.

## Workshops

Workshops are common for eliciting expert knowledge, for example, in information science or design fields (Thoring et al., 2020) or for policymaking (Scapolo & Miles, 2006). They can also be used in the design and evaluation of artefacts (Thoring et al., 2020), which is how they were used in this study.

The workshops aimed to elicit the experience and opinions from experts, in the form of local and regional flood risk managers and CI operators, to evaluate the design of the AB-CEM. A group discussion format was chosen, as it is recommended for eliciting participants' opinions and ideas in workshops, along with interviews and questionnaires (Thoring et al., 2020). Five guided group discussions were held on focal topic(s) with 7-11 experts and participating stakeholders from various administrative levels and organisations such as county administrative boards, municipal CI operators and MSB. In total, 21 different experts and stakeholders were involved in the workshops.

## Paper III – A case study on maturity of flood risk assessments

A case study design was chosen in Paper III to investigate how flood risk assessments in Sweden are performed and how cascading effects are considered. Case studies study a specific process and phenomenon in its natural environment using multiple data sources (Creswell & Poth, 2018; Yin, 2014). The selection of methods in a case study can vary and needs to be adapted to the naturally occurring data sources (Hyett et al., 2014). In this case, reports and respondents involved in the Swedish flood risk management process were used as data sources. The data was extracted using qualitative content analysis and interviews, which are explained further in the following sections.

### Qualitative content analysis

The methodology section for Paper I described the general aspects of qualitative content analysis. Therefore, it is not included here. The purpose of the study in Paper III was to evaluate the quality of three components of flood risk assessments in Sweden using flood risk assessment reports and flood risk management plans as data sources. To achieve this, a maturity framework with criteria for the quality of risk assessments was developed based on existing quantitative risk assessment literature (Goerlandt et al., 2017; Rae et al., 2014; Rouhiainen, 1992; Zeng & Zio, 2017). The documents were coded using the maturity framework, meaning that the directed approach to qualitative content analysis (Hsieh & Shannon, 2005) was used in Paper III. To reduce potential intercoder variability, a few reports were selected for double-coding and were thereby reviewed by both authors.

The data consisted of 55 flood hazard reports and 43 flood risk management plans collected from county administrative boards, MSB and the Swedish Meteorological and Hydrological Institute. It covered two FD cycles (2009-2015 and 2016-2021), making it possible to study longitudinal changes. The dataset can be considered complete, as it contains all reports and plans produced as a part of the FD in Sweden for these two cycles.

### Interviews

Interviews are widely used as a method for gathering data in various research fields (Qu & Dumay, 2011; Rowley, 2012). Interviews are conducted through a one-on-one interaction between the interviewer and the interviewee and allow for the collection of rich, detailed, and nuanced data. Interviews can be structured, semi-structured, or unstructured, depending on the study (Kvale, 2007). They can be conducted in person, over the phone, or with online tools like video conferences. The advantages of using interviews as a research method include the ability to probe deeper into respondents' experiences, perspectives, and attitudes and the potential for the interviewer to build a rapport with the interviewee that can lead to more insightful responses.

In Paper III, interviews were used to complement the content analysis and gain a deeper understanding of flood risk managers' challenges when assessing flood consequences and cascading effects. The aim was to interview all 12 County Administrative Boards (CABs) that developed flood risk management plans in the first FD cycle and MSB. 10 CABs and MSB accepted the invitation. Because the interviews were exploratory and we expected diverse answers, a semi-structured format was used (Galletta, 2020; Kallio et al., 2016). The interviews started with a brief problem description to establish a shared understanding of the concepts and context. The interviews covered three themes (assessing direct consequences, assessing indirect consequences (cascading effects), and GIS), followed by additional prepared questions and ad hoc follow-up questions that arose as the interview progressed. All interviews were held over video conference calls (due to Covid-19) and were recorded and transcribed. After the interviews, the respondents received the transcription for review, and no amendments were made.

## Paper IV – Simulated experiment of critical infrastructure and information sharing

Paper IV aimed to study how different levels of information on interdependencies in complex and interconnected system-of-systems affect the ability to identify vulnerabilities. The fundamental idea of the paper was to investigate how the outcome of a vulnerability analysis would vary depending on which type of CI is being studied and the level of information regarding interdependencies. This type of problem formulation, where a few variables are actively changed, is generally suitable for classical experiments (Ö. Andersson, 2012). However, it is generally difficult for a researcher to perform such experiments for real-life CIs. CIs always need to be functional, and intentionally lowering the functionality as an experiment requires careful consideration, planning, and permission from CI operators, which is normally only feasible for experiments on a limited scale. Additionally, experiments can be costly in terms of lost productivity and can, in some cases, potentially cause direct harm to human health. Therefore, the only viable option was a simulated experiment using computer modelling and simulation techniques. A simulated experiment follows the same foundational principles as a classical experiment but in a modelled environment instead of a physical environment.

## Modelling and simulation

Modelling and simulation (M&S) is a well-recognised method within the engineering discipline and has been widely applied in CIR research (Ouyang, 2014; Yusta et al., 2011). Modelling involves the construction of a simplified representation of a real-world system, and simulation involves using computer algorithms to simulate the behaviour of the model under different conditions.

The advantages of using M&S as a research method include the ability to test hypotheses and explore scenarios in a cost-effective and efficient manner (Padilla et al., 2011). M&S can also provide insights into complex systems that are difficult to study through other research methods (Carson, 2005). M&S also allows experimentation with systems which would otherwise be too costly, dangerous, disruptive or morally objectionable (Birta & Arbez, 2007 Ch. 1.). These aspects make it an attractive method for studying CI systems and behaviour from a CIR perspective. Using M&S, a researcher can safely explore thousands or millions of scenarios in a few hours or days, depending on the size and efficiency of the model and the hardware used to run it.

The accuracy and validity of modelling and simulation results depend on the underlying data quality and assumptions used to construct the model. To ensure the reliability and validity of modelling and simulation results, researchers should carefully calibrate and validate their models using real-world data and empirical evidence when possible (Carson, 2005). It can be challenging to validate data when studying rare events such as natural hazards or large-scale disruptions in critical infrastructure. This is because there may not be enough data points available for validation. For instance, in Paper IV, the Swedish transmission system has only experienced two major failures in modern times: once in 1983 and once in 2003 (Energimyndigheten, 2006; Svenska Kraftnät, 2009). Researchers should also be transparent about the assumptions and limitations of their models.

In Paper IV, the M&S approach was used to investigate how an awareness of interdependencies impacts the ability to analyse vulnerabilities and cascading effects. The paper also looks at the implications for societal resilience. The study modelled three Swedish national CIs, a power, a fibre, and a railway system, using a supply and demand model. The systems are based on real-world infrastructure data and contain 816 nodes and links divided on the three infrastructures. The model also accounts for dependencies between the systems. The model was verified, i.e., ensuring that the assumptions made were translated correctly to the simulation code (Law, 2015 Ch. 5.), using several techniques such as stress testing, reviewing model output, tracing the logic in subroutines, and reviewing the code. Real-world data and system information were used to the extent it was possible to ensure a reasonably valid model, i.e., an accurate representation of the system for the objective of the analysis (Law, 2015 Ch. 5.). The data has been used in several previous studies (Sonesson & Johansson, 2019; Svegrup et al., 2019).

A limitation, however, is that the data is 10-20 years old and has been generalised to reduce the number of components. Naturally, the power system has changed its configuration since 2003. Today, the total load (including exports) is, on average, around 20 000 MW for 2021 compared to the 15 000 MW used in the September 23rd 2003 configuration (Statistics Sweden, 2022). On the generation side, significant investments in new wind generation have been made, and the use of nuclear power has declined (Statistics Sweden, 2022). However, the dataset should remain relevant concerning the overarching questions explored in the paper since the overall topology and dependency relationships remain similar. The railway system has not undergone any significant topological changes since 2012, and the total length of the tracks has not changed significantly (Transport Analysis, 2023). The changes were deemed relatively small and would, therefore, not impact results significantly, as the goal in Paper IV was to study a general phenomenon based on real-world data and not, for example, give specific advice on vulnerabilities to CI operators.

## Vulnerability analysis in CIR

In a CIR context, a vulnerability analysis generally aims to evaluate the magnitude of negative consequences that arise, given a strain on the system (Johansson et al., 2013). By evaluating many scenarios with different strains, they can be compared, and the scenarios with the most detrimental effects on the system can be identified and, if possible, prevented or mitigated. The level of strain can be defined by a concrete scenario, such as a natural hazard of a particular magnitude (taking more of a risk perspective), or by a more abstract measure, such as a combination of failed components, sometimes notated as N-X, where X is the number of failures (taking more of a system weakness perspective) (Johansson et al., 2013). An ideal vulnerability analysis would evaluate all combinations of possible strains, from one component failure (N-1) to all components. However, the number of possible strains increases exponentially with X, which means that it is sometimes not feasible to analyse all levels of strains due to computational cost.

In Paper IV, power, ICT, and railway infrastructures, based on real-world Swedish CI data, were analysed using vulnerability analysis under different strains and conditions. The strain levels varied from N-1 to N-4. For each strain level, the three systems were modelled and simulated under five different conditions, resulting in 15 simulations per strain level. In the five simulated conditions, the systems have either (1) no consideration for cascading effects to other systems, (2) consideration for first-order cascading effects on systems downstream due to interdependencies, (3) consideration for first-order upstream cascading effects that can affect their systems, (4) a combination of both (2) and (3), or (5) full consideration of cascading effects on a system-of-system level.

# Results

This chapter presents the main findings concerning the overall research aim, namely, to contribute knowledge and methods that can be used to support analyses of cascading effects across interdependent CIs. First, the summarised results of the appended papers are presented. It is followed by a thematic summary related to each research question. Square brackets refer to work that I have authored. Majuscule Roman numerals (i.e. [I]) refer to appended papers, and minuscule Roman numerals in square brackets (i.e. [i]) refer to related publications.

## Appended papers

This section presents a short description and a summary of each paper's main findings in order of publication.

### Paper I – Critical infrastructure, geographical information science and risk governance: A systematic cross-field review.

The paper presents a scoping study of scientific journal articles that span the fields of CI, GIScience and RG, particularly the overlap between CI and the other two. Through a novel keyword and a content analysis, it discusses the potential synergies, limitations, challenges, and opportunities for cross-disciplinary research between these fields with the specific aim of how CI research could benefit from GIScience and risk governance.

Although CI, GIScience and RG stem from different policy or academic backgrounds, an overarching similarity is that climate change, flooding, critical infrastructures, risk assessments, vulnerability, decision-making, and sustainable development are central topics for all research fields.

Several potential synergies were identified. For example, conceptual overlaps exist between the fields, such as interdependencies and resilience. There are also potential synergies in using geodata to estimate the impact of natural hazards on CI, compiling geodata sets for supporting CI analyses and using maps to visualise the results of CI analyses. Further, RG case studies could be used to better understand managing risks across interdependent CIs. Although several articles used detailed

CI data, e.g. data that describes the function, capacity relationships or interdependency between CI, the review did not identify any framework or method for identifying and gathering this kind of data. Some limitations of the reviewed literature include the low presence of specific CI sectors such as healthcare, safety and security, finance and food supply and the fact that there are few articles on managing confidentiality in CI research.

The main conclusion is that there is an opportunity to apply several robust analytical toolsets from GIScience to the CI field. Moreover, additional studies are needed to validate the efficacy of RG principles for managing CI. Managing confidential data, strengthening the presence of non-technical CIs in advanced analyses, and harmonising the resilience concepts were identified as the main challenges.

### Paper II – A methodological approach for mapping and analysing cascading effects of flooding events.

This article presents AB-CEM (Area-Based Cascading Effect Method), a method for mapping and analysing the cascading effects of flooding. AB-CEM aims to support local and regional governments in establishing a structured workflow for mapping cascading effects with a practically applicable method. The article is a scientific version of an MSB-commissioned report [vi] and an extended version of a conference paper [vii] on the same topic.

The suggested method provides a general, logical workflow and a structure for collecting essential cascading effect characteristics. It focuses on making local and regional expert knowledge about CI and interdependencies more explicit through interviews and workshops with affected stakeholders. AB-CEM consists of 8 steps: 1) collect input from existing material and experts such as hazard assessments, 2) identify directly affected CIs through the initial hazard assessment, 3) register CI details such as type or affected components, 4) perform a consequence assessment of identified CIs using available experts, 5) identify interdependencies to other CIs, 6) compile a single CI into a form, 7) compile all CIs in database, 8) make an overarching analysis and visualisation. An overview of the method is presented in Figure 6.

The data collection is designed to enable more advanced analyses, for example, by using GIS or network analysis, once enough data has been collected. The suggested structure also allows for reusing mapped data on CI interdependencies to analyse different kinds of hazards, which, in practice, helps reduce workload. AB-CEM also provides some examples for presenting the results, for example, GIS maps and Cascading Effects diagrams.

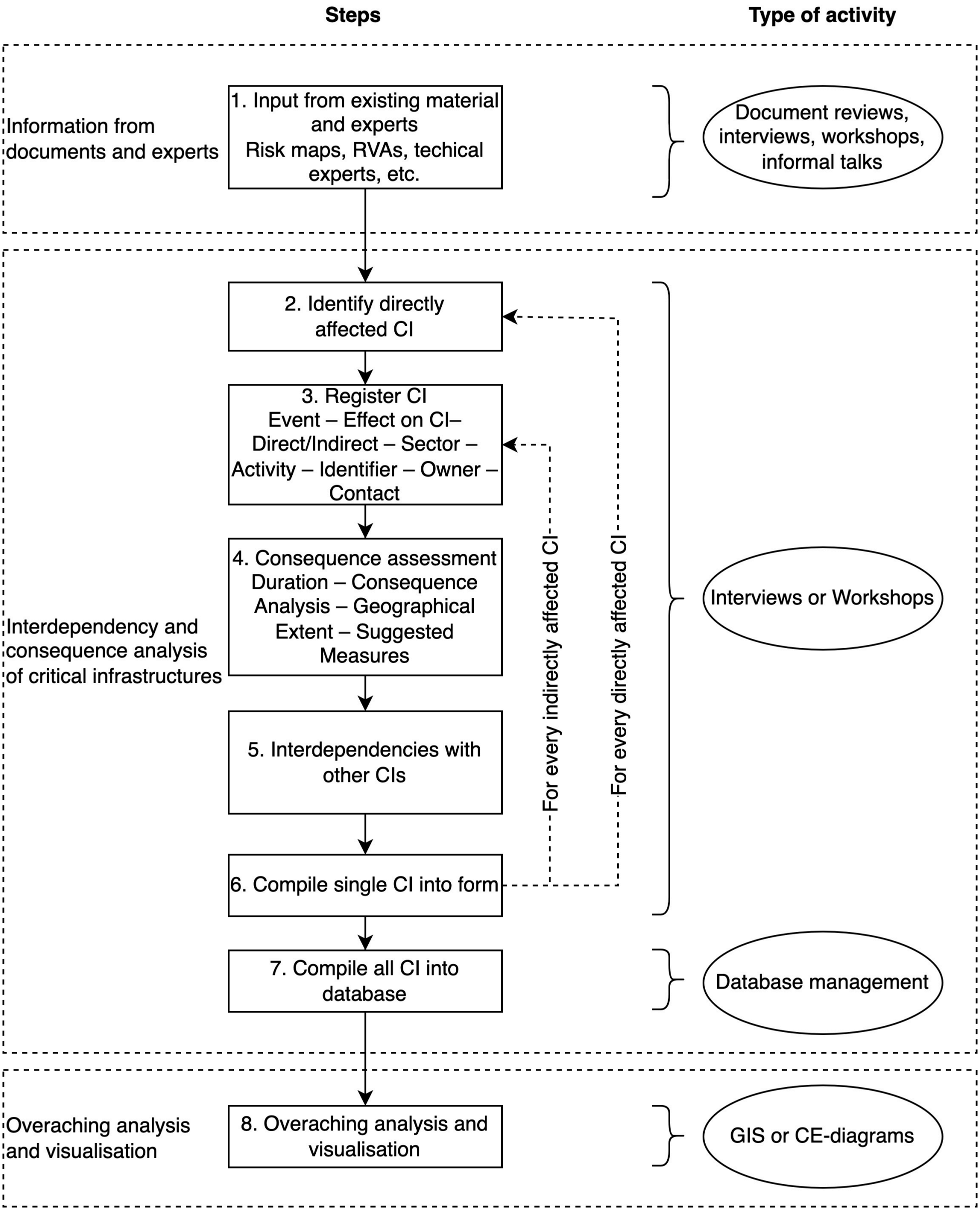


**Figure 6.** An overview of the suggested steps in AB-CEM.

Based on the discussions with stakeholders in the workshops, identifying and analysing interdependencies between critical infrastructures and the cascading effects that can arise during disruptions is a highly relevant problem for Swedish flood risk professionals. The main identified challenge for applying the method was information security, as data on critical infrastructure in an aggregated database is often considered confidential. A limited pilot study in the form of a master thesis (Andersson & Carlström, 2020) successfully applied AB-CEM in both flood and drought scenarios. The pilot study identified several critical interdependencies in Karlshamn, more and in greater detail than is typically identified in municipal risk management plans. An evaluation of the pilot study found that the method was relevant for identifying interdependencies and cascading effects in a municipal setting. However, the evaluation also identified that support for identifying suitable measures and the ease of use in certain aspects could be improved (E. Andersson & Carlström, 2020).

It can be concluded that AB-CEM fulfilled the design criterium of being a practically feasible method for municipal and regional governments to identify and analyse cascading effects that can arise during spatial hazards. Further, it takes advantage of GIS and can be applied to hazards other than floods, which were two other design criteria. However, the paper also highlights a common challenge for risk professionals concerning sensitive and secret data, specifically the conflicting interests of information availability and information security pertaining to critical infrastructures. Although further testing of the method is desired, it is a much-needed step towards integrating cascading effects in Swedish municipal and County Administrative Board (CAB) risk and vulnerability management efforts.

### Paper III – Flood risk assessments – exploring maturity and challenges in Sweden.

The paper includes a comprehensive and longitudinal case study of Swedish flood risk assessments and flood risk management plans from two FD cycles (2009-2015 and 2016-2021). More specifically, the focus is on three critical components of flood risk assessments: flood hazard assessments, direct consequence assessments and indirect consequence (cascading effects) assessments. It evaluates the maturity levels and identifies challenges associated with each type of assessment.

The study found that flood hazard assessments are highly mature, likely due to longer research traditions and well-established practices. Therefore, there are more established methods, tools, data, and expertise to rely on. For example, flood hazard modelling is relatively easy and cheap to outsource to technical consultant companies. The main limitation lies in how uncertainties are presented in the reports.

The direct consequence assessments mainly focus on identifying flooded objects rather than estimating the potential consequences of the disruptions of these objects. For example, they lack damage estimates using depth-damage functions, which have been implemented and supported in some other EU Member States. The notable weaknesses of the reports concerning direct consequences include the lack of descriptions of resource constraints or methods and the low maturity in describing uncertainties. Even though resource constraints were not described in the reports, interviews revealed constraints regarding GIS competence, analytical tools, time, and budget.

The indirect consequence (cascading effects) assessments are the least developed out of the three and scored low in all evaluated maturity criteria. Notably, some respondents argued that assessing indirect consequences was outside the scope of the FD. When indirect consequences are mentioned, they are often limited to internal (CAB) expert judgements and reasoning, which often result in rather vague descriptions such as:

> 'the drivability on the roads will be affected, which can lead to problems for the rescue services to operate in the area' (Länsstyrelsen Örebro län, 2021, p. 24)

The reports also lack method descriptions for indirect consequence assessments. Based on the interviews, accessing relevant CI and interdependency data and keeping that information secure are key challenges CABs face when performing these analyses.

For all three types of assessments, no noticeable change in maturity levels between the two FD cycles (2009-2015 and 2016-2021) was found, which indicates slow progress. However, one explanation could be that the scope of flood hazard assessments in Sweden was expanded in the second cycle to include pluvial and coastal floods. In the first cycle, only fluvial floods were being considered.

In conclusion, there is a great need for practical methods for analysing direct and indirect consequences in flood risk assessments. CABs would also benefit from increased availability of CI functionality and interdependency data, providing further relevance for Paper II. Additionally, providing transparent accounts of resource utilisation, constraints, and uncertainties in flood risk management plans would increase their trustworthiness and usefulness in informing decision-making.

## Paper IV – Exploring the importance of cross-sector information for interdependent critical infrastructure governance.

The article investigates how various levels of consideration of interdependencies and cascading effects change the outcome of vulnerability assessments of CI. It uses real-world data on power, telecommunication, and railway infrastructure to create a model of interdependent CIs. The model simulates both failure scenarios and the levels of consideration for interdependencies and cascading effects. The simulations contain five interdependency consideration levels and four different stress levels in the vulnerability analysis. The simulation results are evaluated from two perspectives: the calculated consequences for the individual CI and the consequences for the system-of-system (SoS).

The results indicate that for CIs with many upstream dependencies, such as railways or ICT, introducing a consideration for upstream dependencies drastically increases the potential number of scenarios in the vulnerability assessment. In other words, it improves the completeness of the vulnerability assessment. It particularly improves the chances of identifying the scenarios with the most severe consequences for the CI. A comprehensive vulnerability assessment is essential for directing risk mitigation efforts to where they are needed.

For CIs with many downstream dependencies, such as power, internalising downstream consequences into the originating CI re-aligns the individual CI consequences to better match the SoS consequences. In other words, when consequences are internalised, high SoS-consequence scenarios also lead to higher consequences for the upstream CIs. Thus, with internalisation, the upstream CI should be more incentivised to mitigate these high SoS-consequence scenarios, leading to an overall higher resilience on the SoS level.

In the model, considering first-order interdependencies and cascading effects produced similar results to the SoS-level for small initial disruptions, such as one or two simultaneous failures, compared to a full SoS-level consideration. However, as the initial disruptions are larger, a smaller and smaller proportion of the scenarios can be included in the vulnerability analyses when only first-order interdependencies and cascading effects are considered. This indicates that a SoS-level consideration is necessary to identify the most severe scenarios.

However, a prerequisite for considering cascading effects is having information about them, which is why sharing cross-sector information is essential for CI governance. This supports the importance of the communication principle in the RG framework. It also highlights the need to find and implement solutions to the challenges related to cross-sector information sharing, such as establishing trusted platforms for sharing information and managing confidentiality.

# Addressing the research questions

This section presents the primary findings based on identified themes related to the three research questions outlined in the thesis, as opposed to the paper structure used previously.

## How are cascading effects between CI identified and assessed in Sweden?

This section presents the findings related to the current state of identifying and assessing cascading effects in a Swedish context.

*Immature consideration of cascading effects*

The findings from the comprehensive review of flood risk management plans and flood hazard reports, a review of Risk and Vulnerability Analyses (RVAs), and interview and workshop findings show that cascading effects are still largely neglected in risk and vulnerability assessments in Sweden [III, iii]. Indirect consequence (cascading effects) assessments were the least mature part of the flood risk assessments and less frequently followed a systematic method than assessing the flood hazard or direct consequences [III]. A similar trend was found in RVAs, where only a few reports followed a specific method for assessing interdependencies and cascading effects [iii]. Additionally, cascading effects are less frequently quantified and more frequently described qualitatively using vague expressions such as 'affected' [III]. These findings are also consistent with the RVA study, which found that interdependencies are often vaguely described and rarely justified, and indirect consequences (cascading effects) are seldom quantified [iii].

*Existing awareness of cascading effects*

Despite the flaws in considering cascading effects, overall, there is a broad awareness of the importance of interdependencies and cascading effects among the authorities responsible for flood risk management and CI operators in Sweden [II, III, vi]. During workshops [II] and interviews [III], many government professionals also expressed that it is essential to consider cascading effects in flood risk assessments. For example, in conjunction with Paper III, one respondent mentioned cascading effects as necessary for the continuity planning of societal functions in municipalities. However, some disagree that they are responsible for going into such detail in their flood risk assessments [III]. One respondent in the interviews related to Paper III argued that it was up to the stakeholders directly affected by the flood to evaluate the potential cascading effects. Hence, there are different views on the distribution of responsibilities for assessing interdependencies and cascading effects, perhaps due to unclear incentives. It should be noted that MSB regards assessing cascading effects as a part of the FD flood risk assessments [III].

*Focus on individual systems and sectors*

The content analysis of flood risk documents and RVAs, workshops, and interviews with flood risk professionals show that, in practice, CIs are still largely managed or treated as individual systems or sectors rather than an interconnected system-of-system when assessing consequences [II, III, iii]. Thus, the system-of-system perspective appears lacking in risk assessments. This is also true from an international perspective; in academic CI literature, the system-of-system perspective only constitutes a small part of the research body [I]. Similarly, in related fields such as supply chain risk management, there is a need for further research on interdependencies and cascading effects [v].

*Slow progress for including cascading effects*

The maturity of flood risk assessments in Sweden was evaluated based on documents from two different FD cycles, which allows for a longitudinal comparison [III]. The comparison showed no significant change in maturity levels between the two FD cycles, indicating slow progress [III]. However, the first FD cycle only considered fluvial flood risk, while the second added coastal and pluvial flood risk scenarios. This may have hindered the CAB's ability to make other improvements to the flood risk assessments [III]. Another finding is that there are several similarities between the RVAs from 2011 and 2013 [iii] and flood risk management plans in 2021 [III] in assessing cascading effects and the associated challenges. The central findings in both publications are that there is a lack of methods for identifying and analysing interdependencies and challenges with accessing data and working with potentially confidential information. This further indicates slow progress.

*Promising Swedish initiative*

Reviewing existing flood risk assessments and methods in Paper II uncovered a promising initiative for including cascading effects in flood risk assessments. In a flood risk assessment of the third largest lake in Sweden (Mälaren), *Mälaruppdraget*, the analysis goes deeper into assessing infrastructure damages in a flood risk assessment (MSB, 2012). For example, significant data collection was initiated to measure the precise elevation of the building for CIs around the lake. This data was used to establish failure threshold values with CI operators and experts. CI operators and experts were also consulted to map dependencies between critical infrastructure. The data was integrated into the analysis, where cascading effects were identified in several scenarios. However, due to security concerns, some parts of the detailed results were not published, and the collected data was destroyed after the completion of the project. This example also highlights a challenge with addressing interdependencies and cascading effects in terms of the amount of resources and time necessary to conduct in-depth analyses.

## What challenges do actors face when assessing cascading effects in a CI context?

This section summarises the findings that relate to challenges for assessing cascading effects.

*Lack of suitable methods*

From interacting with flood risk managers and CI operators in Sweden, it quickly became evident that there is a need for methods for gathering information and for analysing cascading effects that are feasible for local and regional governments [II, III, vi]. Although there are available methods used in scientific settings [I], they often require significant CI interdependency data and expertise in, for example, engineering, mathematics, and computer science that might not be available on a county or municipal level [III]

*Data unavailability*

The review of available CI data in Sweden shows that even for national agencies, access to high-quality and relevant data for analysing the consequences of CI disruptions is limited [viii]. Even when some data is available, necessary characteristics for analysing CI and cascading effects are missing [III, viii]. For example, one of the missing characteristics is threshold values when failures occur for different hazards (i.e. specific water levels for floods, wind speeds for storms, or seismic energy for earthquakes), similar to the water levels used in *Mälaruppdraget* (MSB, 2012). These thresholds can be used to determine the direct effects on CIs, which is a necessary prerequisite for analysing cascading effects. Other missing characteristics relate to interdependencies, such as how dependent CIs would be affected by upstream failures [III].

*National security and confidentiality*

One of the most apparent challenges that were brought up by stakeholders in workshops [II, vi] and interviews [III], and in the reviewed CI literature [I] is the conflict between sharing cross-sector information for better decision support on one hand and national security or confidentiality concerns on the other hand. Several professionals in municipalities, CABs, and CI operators experience a lack of guidelines in this regard [II, III, vi]. A concrete example of issues arising from confidentiality is that aggregating CI data in a database will increase its secrecy level, even though the data of individual CI have a lower secrecy level. This forces CABs to work offline, drastically hindering the typical workflow of the analysts [III]. For example, updating the information in the database must also be done offline, potentially requiring sending physical storage devices by courier. Similarly, some software requires an online connection to update and verify licences. Thus, even if CABs manage to persuade CI operators to share less confidential data, it might become, as one respondent put it, 'too hard to work with if the data is too good' [III] because the data gets aggregated and, therefore, more confidential.

Confidentiality concerns also became apparent when AB-CEM was tested. Although the master's students successfully tested and evaluated AB-CEM, they did experience some reluctance to share potentially sensitive information from some of the participating stakeholders, even with support from the local municipality [II]. For example, the estimated duration of district heating failure in case of a flood, the exact placements of district heating backup systems, or the municipal emergency plans for the distribution of potable water were deemed too sensitive to discuss (E. Andersson & Carlström, 2020).

*Unclear benefits of assessing cascading effects*

In Paper III, although most respondents saw the value of analysing cascading effects in flood risk management plans, a few CAB respondents questioned if it was necessary. This highlights a potential underlying challenge to include cascading effects in risk assessments: it is currently difficult to assess the added value of the extra analytical work needed. On the other hand, the extra work costs are relatively easy to estimate. In other words, uncertain benefits and tangible costs are associated with assessing cascading effects. Therefore, this might affect initial decisions that practitioners face in their analysis process: How detailed does the assessment need to be, and how much resources are we willing to spend on it?

*Limited resources and mandate*

Even if methods for gathering and analysing cascading effects are available and concerns about sharing data have been solved, allocating the necessary budget, man-hours, and relevant competence is also a significant challenge for many CABs [III]. This limitation was exaggerated during the second FD cycle when several of the interviewed CAB professionals had to prioritise the crisis management of COVID-19.

Even though CABs and Swedish municipalities have control over land use planning, they cannot force, for example, CI operators or property owners to take preventive measures to mitigate flood risk (SFS 2009:956) [III]. This appears to lead to some frustration among CABs since all they can do is provide recommendations and hope that CI operators and owners think it is worthwhile to implement measures (Länsstyrelsen Skåne, 2015). In other words, authorities have limited mandates and resources to direct flood risk efforts.

*Quantifying consequences*

Both flood risk management plans and RVAs frequently contain vague expressions such as 'the drivability on the roads will be affected' and rarely quantify results beyond this level [III, ii]. The previously mentioned challenges are all possible contributors to why this tendency exists. Describing consequences using qualitative expressions is sometimes necessary, for example, due to lack of data or resource constraints, and must still be addressed or weighted into the assessment. However, relying solely on qualitative assessments can make it challenging to use the assessments for further analyses, such as cost-benefit analyses for evaluating potential measures. Additionally, the FD states that the flood risk management plans 'shall take into account relevant aspects such as costs and benefits' of the suggested measures (European Commission, 2007, Article 7, §3), which is difficult without some form of quantitative assessment.

### How can the assessment of cascading effects between CIs be improved, better incentivised, and more utilised?

The thesis has revealed several challenges related to analysing cascading effects. This section presents findings relating to addressing these challenges, which would help improve the assessment of cascading effects.

*Developing feasible methods to apply with limited resources*

One of the significant challenges Swedish municipal and CAB risk assessment professionals face is finding methods for assessing cascading effects that suit their context. Paper II aimed to address this challenge by introducing a method, AB-CEM (further described in the previous section on Paper II), to systematically gather information on dependencies and cascading effects. It was developed to be feasible to implement and to fit the needs of local and regional flood risk managers in Sweden. AB-CEM provides guidance on the necessary steps, from initial identification to overarching analysis and visualisation, and suggests suitable activities for each step. Implementing and using this method for flood risk assessments would likely improve the maturity level of assessing cascading effects.

*National effort to gather data on CIs and interdependencies*

Although relatively large datasets on national critical infrastructure characteristics are available in open-access geodatabases, data enabling cascading effects analysis is more challenging to find [viii]. This includes data that can be used to identify where interdependencies between CIs exist, their strength in terms of impact, or their temporal characteristics. This is not an easy task, as interdependency data can be specific to the type of CI or conditional on, for example, weather conditions [i]. The gathered data also must be validated, organised, systematised, and structured to create continuity for future data management [viii]. Having this data readily available for risk assessment professionals on a national level would significantly lower the barrier to including cascading effects in their assessments and thereby increase the utilisation. It appears reasonable to keep such an initiative at a national level since the resources for public risk assessments at the local and regional levels are already limited.

*Establish platforms for secure information sharing.*

Due to national security and confidentiality concerns, CI and interdependency data must also be shared in a secure format to be used effectively. This also aligns with the new CER directive, which mandates that Member States must facilitate voluntary information sharing between CIs.

Based on the modelling and simulation in Paper IV, including more information on interdependencies affected CIs vulnerability assessments in two fundamental ways [IV]. Firstly, information on upstream interdependencies increases the completeness of their assessments [IV]. Secondly, information on downstream interdependencies makes it possible to anticipate and internalise downstream consequences, which helps bring individual CI priorities more in line with system-of-system prioritisation [IV]. Thus, enabling cross-sector information sharing benefits individual CI assessments and system-of-system resilience.

*More explicit guidelines for determining the confidentiality of CI data*

Currently, municipalities, CABs, and CI operators must conduct a confidentiality assessment whenever they are requested to share information. More precise guidelines for determining the confidentiality of CI data would facilitate this process. This was requested during the interviews with flood risk assessment professionals who found the current guidelines unclear [III].

*More example analyses and empirical evidence of cascading effects*

The analysis in Mälaruppdraget (MSB, 2012) is a good example of the value of making the extra effort to identify potential cascading effects since they managed to identify several critical interdependences that could trigger cascading effects during floods. Assessments of this kind can serve as inspiration for including cascading effects in future assessments.

Access to an empirical library of documented accounts of cascading effects could also be beneficial as a learning tool or reference material for risk assessment professionals, CI operators and researchers. From the review of incidents involving cascading effects, there is a tendency in the incident reports to focus heavily on the steps leading up to the event and less on the following cascading effects [i]. An increased effort in documenting cascading effects through a transparent and systematic approach, as proposed in [i], while investigating incidents would be a necessary step towards building such a library.

# Discussion

In this section, I will first examine the validity and generalisability of the findings in this thesis and compare them with other scientific literature. In the second part, I will discuss the thesis's overall research strategy and scope. The third part will discuss some implications for flood risk and CI policy, followed by pressing avenues for further research. Lastly, I will discuss the cascading effects and their implications for risk and vulnerability analyses.

## Validity and reliability of findings

This thesis has found that the identification and assessment of cascading effects in Sweden is lacking in both scope and depth in flood risk assessments and other types of risk- and vulnerability analyses [III, iii]. This finding is partly based on document analyses, which are vulnerable to biases in the coding phase. This affects the reliability of the results, as two coders might score documents differently due to biases. To combat this, all studies involved double-coding some documents to identify and address coder differences. However, the document studies are based on a large sample (128 reports, plans, and assessments). Additionally, interviewees and workshop attendants admitted that they have not managed to come as far as they would like when assessing cascading effects [II, III]. This triangulation of evidence supports the validity of the finding. The finding is also supported by another study on Swedish flood risk management, which found that cascading effects (or indirect consequences, as the authors phrase it) were lacking in flood risk assessments (Norén et al., 2016). National flood risk assessments in Denmark and Scotland also reveal a lack of consideration of cascading effects (Kystdirektoratet, 2015; SEPA, 2015). The finding is based on publicly available analyses; as such, there might be classified ones that consider cascading effects well. If these analyses exist, it is reasonable that they are confidential due to their higher level of detail in describing interdependencies and cascading effects. If this is true, then the maturity of identifying and assessing cascading effects could be underestimated in this thesis. However, the existence of such classified analyses can likely be discounted, given that they were not mentioned in the workshops and interviews with practitioners during the thesis work. One way to increase the generalisability of this finding would be to replicate the study in Paper III for other countries.

All participating stakeholders in Papers II and III expressed an awareness of the relevance and importance of cascading effects in risk and vulnerability assessments. Cascading effects are also recognised in both CI literature (Brown et al., 2004; Hokstad et al., 2012; Kotzanikolaou et al., 2013; McDaniels et al., 2007; Rinaldi et al., 2001) and flood risk assessment literature (Fekete, 2019; Haraguchi & Kim, 2016; Nones & Pescaroli, 2016). From a policy perspective, the recent CER directive, for example, emphasises the need to identify interdependencies and potential cascading effects (European Commission, 2022b). One of the drivers for issuing the new directive was that an evaluation of the ECI directive came to the conclusion that Member States did not adequately address the cascading effects (European Commission, 2020). Thus, unawareness of cascading effects is likely not a major contributor to the lack of consideration of them in risk and vulnerability assessments but rather points to more fundamental challenges towards addressing them.

The document analyses of flood risk assessments [III] and risk and vulnerability assessment [iii] show a focus on individual systems or sectors rather than a system-of-system perspective. This finding is corroborated by a study on Swedish CI governance, which found that CIs are subject to clear silo structures (Rydén Sonesson et al., 2021). This phenomenon can also generally be discerned in CI research. For example, in Paper I, most reviewed articles studied an individual CI. One explanation could be that sector-specific regulations put an equal or higher demand for risk and vulnerability management compared to the former ECI directive (European Commission, 2020). However, the new CER attempts to take a more holistic perspective on CI resilience, meaning that the requirements should be more coherent across different sectors.

The slow progress of including cascading effects in assessments is supported by the fact that there were no significant changes in maturity between FD cycles 1 and 2 [III]. Additionally, several issues, such as data and confidentiality challenges, were found for the FD in 2021, which was identified for RVAs almost a decade earlier [iii]. These studies are limited to a document analysis of final reports; therefore, they might miss other important improvements in the risk and vulnerability management process. For example, a 3.5-year longitudinal study on risk management processes in a Swedish municipality found that management commitment declined over the study period (Cedergren et al., 2022). A lack of long-term commitment from, for example, County Administrative Board (CAB) managers could explain the slow progress in the flood risk management plans.

One reason for the lack of consideration of cascading effects is the lack of suitable methods for data gathering and analysis, which was expressed in workshops [II] and interviews [III] with stakeholders. The studies, all together, involved more than 50 stakeholders from local and regional government and CI operators in several parts of Sweden. Additionally, the FD-related documents studied in Paper III did not describe any particular methodology for identifying or analysing cascading effects.

If methods had been applied successfully, it is unlikely that they would not have been identified in the interviews or through the documents. Further, the literature review in Paper I did not reveal any method suitable in the Swedish local or regional governmental context. In the scientific literature, some methods consider cascading effects in risk and vulnerability assessments (see, e.g., Ouyang (2014), Yusta et al. (2011), or Sun et al. (2022) for a review of methods). However, these methods are not particularly adapted for a setting where data and resources, like software or specialised knowledge, might be scarce. In conclusion, a lack of suitable methods is likely a valid finding and generalisable outside the Swedish context.

The data unavailability challenge was initially identified in interviews [III] with stakeholders, which is limited empirical evidence by itself. A complementing study reviewed publicly available databases with CI information and found that they rarely contain datasets necessary for assessing direct consequences or cascading effects [viii]. Since this study only reviewed publicly available databases, there might be closed databases containing more detailed information. Apart from potential governmental or CI operator databases, there are commercial databases on, for example, energy and commodity pricing (Shih et al., 2009) that may be useful for assessing the consequences of cascading effects. Since we did not have access to these kinds of databases, it limits the conclusions that can be drawn. However, from a CAB perspective, accessing these databases might be feasible [III]. On the other hand, gaining access might also require effort and resources beyond the limits of CABs.

The challenge of satisfying national security and confidentiality guidelines when acquiring data useful for assessing cascading effects was identified in papers I, II and III. It has also been more broadly recognised in the scientific literature (Alcaraz & Zeadally, 2015). For example, there is a need to balance information sharing and protecting sensitive information (Brem, 2015). This challenge does not only affect stakeholders such as professionals in municipalities, CABs, and CI operators, but it can also affect research outputs. Several strategies used by researchers to include confidential data in their studies were identified in Paper I. For example, studies had to 1) not disclose the study location (Mazri et al., 2014; Zhang et al., 2018), 2) use partly redacted data (Shih et al., 2009), or 3) masque the exact locations and capabilities of facilities (Grubesic & Murray, 2006). These kinds of measures lower the transparency of the studies, potentially making it more difficult to evaluate the relevance and validity of their findings.

The unclear or intangible benefits of assessing cascading effects are only supported by a few responses in the interviews in Paper III. As a parallel, the intangible nature of risk is a rather common issue in risk management (Hubbard, 2020). This issue is also related to the challenge of limited resources since one way to draw more resources to risk and vulnerability assessments, in general, would be to present the potential benefits of this activity. Having limited resources is a fundamental challenge not only in a risk management setting but also in addressing cascading effects. In fact, the problem of distributing resources is as old as civilisation itself and is the fundamental problem of economics. If the value of assessing cascading effects can be shown more tangibly, then it is easier to argue for a better allocation of resources to this activity. Using simulated experiments, such as in Paper IV, is one way to address this challenge.

The study on both Floods Directive [III] and risk and vulnerability analyses [iii] found that consequences are often not quantified. A contributing factor might be the lack of data necessary to do so. Although quantitative risk analyses have been criticised for overselling their value (Rae et al., 2014), there is also an argument for their use, for example, when it comes to prioritising mitigation measures (Apostolakis, 2004). In the end, the goal of the Floods Directive is to prioritise and implement mitigating measures through cost and benefit analyses (European Commission, 2007). Thus, the challenge is likely valid in the context of European flood risk management.

One way to improve the assessment of cascading effects is to make more straightforward yet scientifically grounded methods available for professionals, which was the aim of AB-CEM [II]. As discussed in the challenges section, most available methods have data and analysis requirements that are too high for a local or regional governmental context. This is the methodological gap that AB-CEM aims to fill. The method most comparable to AB-CEM is likely the CIrcle workshop methodology (Deltares, 2023; Hounjet et al., 2016). In CIrcle workshops, stakeholders such as CI experts collaborate to model dependencies between CI using touch tables and GIS software to input and visualise data. The methods are similar in their aim to elicit expert knowledge on interdependencies and cascading effects. However, AB-CEM provides a more encompassing approach to identifying and analysing cascading effects by including previously documented data and relevant analyses, whereas CIrcle focuses only on expert elicitation. AB-CEM was successfully applied to a flood and drought scenario in a medium-sized municipality in Sweden and identified several interdependencies and potential cascading effects (E. Andersson & Carlström, 2020). However, AB-CEM needs further validation since one case is too limited even though the method was developed using a design science approach and in collaboration with several stakeholders. For example, the method could be applied in more municipalities or counties and for hazards other than floods or drought. Further integration of methods and analyses from GIScience would be an exciting venue for further development.

Making CI data more readily available addresses the data unavailability challenge mentioned earlier and allows for more advanced analyses of assessing cascading effects. One way to achieve this is to make a national effort to gather data on CI and interdependencies. Such initiatives exist in, for example, the US (CISA, 2023) and the UK (National Infrastructure Commission, 2024). A challenge with these kinds of databases could be to navigate different jurisdictions and regulations governing the data (Haraguchi & Kim, 2016) and another to manage inconsistencies, incompleteness, and ambiguity among various data sources when integrating them into one database (Shih et al., 2009).

Paper IV shows that establishing trusted platforms for sharing CI data is critical to improving our ability to analyse cascading effects in the long run. This is also supported by the new CER directive and recommendations from the Organisation for Economic Co-operation and Development, OECD (European Commission, 2022b; OECD, 2019). However, any implementation must be considered carefully, as such a system would likely be a tempting target for hacking groups or foreign intelligence agencies. Likely, the access needs to be limited to a national authority mandated to analyse cross-sectoral perspectives of CIs, as has been established in, for example, the United States (CISA, 2023). Such an agency could serve in an advisory capacity for CABs or CI operators or be given more significant responsibility for system-of-system analysis and governance of national CIs.

In Paper III, CAB stakeholders suggested more explicit guidelines for managing confidential information as a potential way to make it easier for CABs to work with CI data. Since the finding is based on the opinions of only a few respondents, the validity can be questioned. However, if it can help address the confidentiality challenge, it might be worthwhile to investigate further.

Except for Paper I, the studies presented in this thesis primarily focus on the Swedish context. Therefore, whether the findings are generalisable to other contexts may not be immediately apparent. However, there are a few reasons to believe they are generalisable to different contexts. Firstly, the findings are deemed relevant to the European FD and CER directives, which other European Union Member States also have implemented. As a result, some of the findings should also be relevant to those states. Secondly, despite the specific differences in standards and technical solutions, critical infrastructures are built based on similar principles in many countries worldwide. Therefore, the insights gained from this study may well be relevant in other contexts. Finally, all countries have administrative boundaries and organisational levels, which means that confidentiality and information-sharing issues are likely more general problems even outside of Sweden.

## Dimensions of research contributions

The research aim of this thesis was to contribute knowledge and methods that can be used to support analyses of cascading effects involving interdependent CIs. The strategy of this thesis was to investigate the topic from a broad range of dimensions rather than addressing a specific dimension of cascading effects. This was a natural first step since cascading effects is still a rather unexplored research field. Once the body of research has grown, more narrow research focuses will likely be explored in the field.

The first dimension was one of *descriptive versus normative* research. A descriptive approach generally aims to answer the question ‘What is?’. In this category, the thesis contributed with a case study of the current state of flood risk assessments and related challenges in Sweden [III]. Insights from this study supported the research aim by identifying ways to improve the analyses of cascading effects and by guiding the development of new methods. Additionally, the scoping study describes the differences and similarities between the three research fields. It identifies opportunities for incorporating knowledge or new methods from the RG and GIScience fields into the CI field [I]. Although there are literature reviews in the CI field (e.g. on modelling methods (Ouyang, 2014) and CI resilience (Liu et al., 2022)), this review took a novel approach by looking beyond the CI field for interdisciplinary research opportunities. The related publications on the current state of risk- and vulnerability analyses in Sweden [iii] and CI data availability [viii] also fall into the descriptive category. A normative approach instead aims to answer the questions ‘How should?’ or ‘How must?’. The paper on developing AB-CEM [II] took this approach by suggesting a method for mapping and analysing interdependencies and cascading effects in risk assessments. The simulated experiment on CIs [IV] also took a normative approach by exploring different levels of considerations for cascading effects and the implications this has on CI governance. The related publication on a method for gathering and structuring data information on cascading effects after a crisis [i] also falls into the normative category.

The second dimension was *theoretical versus practical* aspects of cascading effects. For example, in the scoping study in Paper I, I identified several potential areas where the CI research field could borrow methods or ideas from the GIScience and RG research fields. However, the paper mainly focused on theoretical aspects rather than practical ones. Similarly, Paper IV used theoretical models to examine the impact of information sharing on vulnerability assessments of CIs. Even though the models incorporated real-world data, and the results had implications for CI governance, the study's starting point was highly theoretical. Similar studies have been done in the supply chain management field (H. Li et al., 2017), but it is a novel approach in the CI field. In contrast, the two papers on flood risk assessments [II, III] focused on the practical issues of considering cascading effects. The purpose of AB-CEM was to be used in a practical setting to assess cascading effects in flood risk assessments [II]. The case study evaluates one of the practical outputs from the FD, namely, consequence assessments [III], which generally have been lacking in flood risk assessments (Merz et al., 2010). Additionally, it contributed to a more in-depth evaluation of flood risk assessments compared to previous Swedish studies on flood risk assessments, such as Norén et al. (2016), which had a larger focus on, for example, organisational aspects.

A third dimension was the *geographical and administrative levels* addressed in the studies. One part of the thesis work focused on cascading effects in risk assessments on the local and regional levels in Sweden [II, III], although national policies and interviews with national authorities are also included in these studies. Paper IV focused on the national level by using datasets and governance of national CIs. The policies most relevant for the thesis were the Floods and CER directives, which are administrated at the EU, national, and regional levels. Thus, this thesis has studied cascading effects on several geographical and administrative levels.

A fourth dimension was that the thesis demonstrated both *relatively simple* (AB-CEM) [II] and *more complex* (modelling and simulation) [IV] methods for including cascading effects in risk and vulnerability assessment. Although they might have varied in complexity, both methods successfully contributed new knowledge or empirical results relevant to the research aim.

Lastly, the thesis includes a cross-disciplinary research dimension by using a range of methods rooted in *engineering* [II, IV] and *social sciences* [I, II, III]. This broad range of methods was valuable and complemented each other, and I believe this approach was fruitful for the aim of this thesis.

A benefit of addressing the research aim along several dimensions is that it, to some extent, has been possible to triangulate findings. For example, the challenge of sharing confidential information was highlighted in the workshops with local and regional flood risk assessment professionals and CI operators [II], in the interviews with CABs and the national authority MSB [III], and in the scoping study [I]. It has also resulted in the inclusion of many stakeholders in the research process, which should also make the contributions in this thesis valuable for a wider audience.

## Additional contributions

This thesis has made two contributions in areas outside the scope of the primary research aim. The first contribution is the development of a keyword analysis for comparing research fields [I], which relates to systematic literature reviews and scoping studies. Keyword analysis offers a relatively simple way of estimating the degree to which an article belongs to a particular research field. By using a large sample of articles that are confirmed to belong to a research field, a ranking list of the most prevalent keywords can be constructed. Then, any article can be scored based on how high its keywords rank in the research field. Examining and comparing the most prominent keywords used to describe research articles in the research fields can, for example, be used to find overarching similarities and differences between research fields [I]. Using keyword analysis can also be beneficial for reducing bias in the article selection process in literature reviews, as it is based on an algorithm rather than human assessments (Kahneman & Klein, 2009).

The second contribution is a framework for evaluating the maturity of flood risk assessments [III], which contributes to the continuous discourse on what constitutes a high-quality quantitative risk analysis (See, e.g. (Goerlandt et al., 2017; Rae et al., 2014; Rouhiainen, 1992; Zeng & Zio, 2017)). The framework was successfully applied in a case study to evaluate the maturity of three components of flood risk assessments [III], which revealed significant differences between them.

# Recommendations

The case study on Floods Directive (FD) flood risk assessments showed that one component of assessments, i.e. the flood hazard assessment, had a higher maturity than the direct and indirect consequence assessments [III]. We concluded that this is partially due to the high availability of appropriate geodata, methods, tools, and relatively cheap consultant services. In contrast, direct and indirect consequences assessments lacked the availability of one of several of these aspects [III]. This discrepancy highlights the importance of developing and implementing suitable methods and data and making resources available for high-quality risk or vulnerability assessments.

A straightforward recommendation would be to explicitly demand consideration of cascading effects in flood risk management plans, as is done for CIs in the CER. Currently, there is no explicit mention of this in the FD, even though it is implied [III]. From interviews with the authorities responsible for implementing the directive in Sweden, we know that they expect CABs to consider this in their assessments, but some CABs disagree [III]. Putting it as a requirement in the regulating ordinance would clarify this issue. To provide a solid foundation for assessing cascading effects, a good addition to the FD process in Sweden would be to include depth-damage functions in the direct consequence assessment [III]. This has been studied or implemented in, for example, Italy (Albano et al., 2017; Carisi et al., 2018) and Poland (Godyń, 2021). The method is often limited to economic aspects such as property damage, but it would still be a useful component to consider in, for example, cost-benefit analyses. There are already resources available from the Joint Research Centre which provide good guidance (Huizinga et al., 2017).

The simulation study of national CI showed that when CIs are forced to consider the first-order downstream consequences they cause, it aids in mitigating scenarios with high system-of-system consequences [IV]. This approach was inspired by pre-existing examples of such regulation in Sweden's power sector and the aviation sector in the EU (Commission statement, 2004; SFS 1997:857). Hence, the possibility of using regulation to force CI operators to internalise damages they might inflict on CIs or customers, such as penalties or fines, should be investigated. However, the simulation results also showed that considering the first-order cascading effects still has limitations and that a system-of-system perspective is needed to identify and analyse extreme events [IV]. Achieving this likely requires a coordinated, national effort to address the challenges presented in this thesis.

# Further research

As highlighted several times in this thesis, methods that can consider cascading effects in risk and vulnerability assessments are needed. Although one method, AB-CEM, has been developed in this thesis [II], it could be improved with further testing and development. For example, it could be tested for more hazards than floods and drought. However, for different hazards, it might be necessary to use other approaches than the area-based one in AB-CEM. Therefore, it would be interesting to continue developing and testing methods that include cascading effects in risk and vulnerability assessments.

One of the challenges for CI risk and vulnerability assessments is to find a balance between the value of completeness and quality of the assessments on the one hand and the resources needed on the other hand. This is a fundamentally interesting question for all kinds of risk assessments since investing resources into the risk analysis often reduces the resources that can be used to mitigate the risk. In the context of this thesis, this could be formulated as: What is the added value of considering cascading effect in risk or vulnerability assessments? I believe that the findings of Paper IV contribute to this question, highlighting the importance of considering interdependencies and cascading effects on a system-of-system level for improving societal resilience. However, it is a complex question, and more studies are needed.

Paper IV showed that if information on potential cascading effects is available, CI operators can better identify catastrophic scenarios in their vulnerability assessments. This information could be used to reduce vulnerabilities and improve the overall CI resilience in society. At the same time, in the wrong hands, the same information could be used to plan more effective attacks on CIs and potentially increase the overall vulnerability. The danger of leaking information on critical infrastructure to hostile actors is evident and often discussed. However, the danger of not sharing information between critical infrastructure operators to ensure safe, reliable, and robust operations at a system-of-system level is less discussed and is a fascinating question for further research.

In Paper I, several potential synergies between CI and GIScience were identified, such as using GIS for spatial analysis of CIs or collecting data on impacts from natural hazards [I]. We also identified studies where GIS were used for network analysis and simulation of CIs (Espada et al., 2015; Fekete et al., 2017; Jenelius et al., 2006; Shih et al., 2009; Yates & Casas, 2012) [I]. AB-CEM was designed to gather data that can be used for spatial analyses of cascading effects in CIs [II]. In

Sweden, most governmental institutions have access to and use GIS daily; for example, CABs have a shared online geodata service [III]. GIS is also commonly used among CI operators. This means that many of the actors that perform risk and vulnerability assessments have experience with GIS. Thus, it is an interesting direction for further research on the integration and development of GIS tools in a CI resilience context.

## Implications of cascading effects for risk and vulnerability assessments

One argument for including cascading effects is that it leads to more correct consequence assessments. If potential cascading effects are not assessed, the impacts of risks or vulnerabilities in CIs might be severely underestimated (Koks et al., 2019). For example, water damage to infrastructure is important in flood events, but they are rarely the only consequence. In the aftermath of Hurricane Sandy in New York in 2012, researchers found that the direct flood water damages to the electricity, transportation, healthcare and building sectors were about 80, 35, 75 and 30 % of the total damages, respectively (Haraguchi & Kim, 2016). The other damages, i.e. 20-70 %, were due to interdependencies between CIs, such as loss of electricity for the subway system, fuel shortage due to fuel facility damage, blocked bus roads, and more (Haraguchi & Kim, 2016). When investing in CI resilience, underestimating the risks or vulnerabilities might mean the most severe threats are overlooked.

In Paper IV, we showed that including only the first-order upstream dependencies in CI vulnerability analysis significantly increases the number of possible scenarios that can be assessed. A complete system-of-system analysis has an even more significant effect since it can also consider higher-order cascading effects. Having a wide range of scenarios is helpful for the simple reason that it is challenging to manage risks that have not been identified. We also found that the scenarios with the most severe consequences all had many activated dependencies. Thus, by omitting cascading effects, it is not the average scenarios that are missed; it is the scenarios with the most severe consequences. It is difficult to argue that it is possible to make CI resilient if the most devastating risk scenarios are not accounted for.

However, there is a necessary trade-off, as it generally takes more time and resources to include more scenarios in risk or vulnerability analyses. Including more scenarios in a traditional risk analysis might result in more research time, more calculations, and longer reports to write. One of the main limitations is having enough computational resources for the kind of vulnerability analysis performed in Paper IV. Although the simulations in Paper IV are rather efficient at about half a second per scenario, the number of possible scenarios in the vulnerability analysis rises exponentially as the number of failures increases. For example, a complete evaluation of N-3 (i.e. three simultaneous random failures) would take about 500 days to complete compared to about 40 hours for N-2, assuming the same computational speed and CI system configurations (and ignoring other potential issues that can arise with such demanding computational problems). As the complexity of the model and the extent or number of CI systems increases, so do the expected simulation times.

Another potential benefit of including cascading effects in assessments lies on an organisational level. If organisations must identify and assess dependencies to and from other stakeholders, they also must initiate some form of dialogue with them. This aligns with risk governance principles as it would include a more diverse set of stakeholders with a broader range of knowledge in the analysis process (van Asselt & Renn, 2011). Dialogues also create opportunities for building inter-organisational networks and trust (Månsson, 2019), which can act as a lubricant for organising collective actions to deal with shared problems such as interconnected risks (i.e. cascading effects) (Bekkers & Thaens, 2005).

To summarise, if cascading effects are ignored in risk and vulnerability analyses, many consequences could be unaccounted for, particularly for the most severe scenarios. The activity of assessing cascading effects also might come with additional benefits for building resilience, such as creating social networks between, for example, critical infrastructure operators.

# Conclusion

This thesis contributes towards an increased understanding and consideration of cascading effects due to interdependencies between critical infrastructures. It has used several scientific methods to investigate this topic from various perspectives.

The thesis found that Swedish risk and vulnerability assessments rarely identify and assess cascading effects. However, many stakeholders, such as local and regional flood risk professionals, CI operators, and the Swedish Civil Contingencies Agency, are aware of the importance of doing so. Nevertheless, CIs are often treated as stand-alone systems in the reports, which makes it difficult to identify cascading effects. Further, a longitudinal study of Swedish flood risk management plans indicates slow progress towards including cascading effects, which needs to be addressed.

Towards this, the thesis also identifies several challenges in assessing cascading effects in risk and vulnerability assessments. Most prominently, local, regional and national flood risk and crisis professionals lack methods to identify and analyse interdependencies and cascading effects that are feasible with the available time and resources. Furthermore, getting access to data to support these analyses is challenging. Another prominent challenge relates to national security and confidentiality, which can hinder stakeholders from accessing data necessary for assessing cascading effects. A general challenge is getting enough resources and time to extend risk or vulnerability analyses beyond the direct consequences. A likely contributing factor is that the benefits of assessing cascading effects are intangible and that the extra effort required by stakeholders is rather tangible – to clarify them is an essential venue for further research.

A method (AB-CEM) was developed in this thesis to assist local and regional risk analysts in identifying and analysing interdependencies and cascading effects. The method was designed to be a simpler yet scientifically grounded alternative for professionals compared to the methods presented in scientific literature. A critical step towards improving the conditions for risk professionals to assess cascading effects is to make a coordinated, national initiative to gather CI and interdependency data. Secure platforms for sharing sensitive CI data should also be established to disseminate this data to relevant stakeholders. Additionally, having more explicit guidelines for handling confidential data would support regional flood risk professionals working with sensitive data. Finally, having access to an empirical library of documented accounts of cascading effects could also help risk professionals identify and assess cascading effects.

From an international research perspective, the cost-effectiveness of performing high-quality and encompassing risk or vulnerability assessments that include cascading effects versus quicker but less thorough assessments is an interesting path to pursue. Similarly, more guidance is needed to choose between the dangers of not sharing information between CI operators to ensure safe, reliable, and robust operations and the threat of leaking confidential information to antagonistic actors.

The thesis emphasises the importance of considering cascading effects in resilience-oriented assessments to ensure comprehensive identification and mitigation of potential risks and vulnerabilities. If cascading effects are ignored, many potential societal impacts could remain unaccounted for, especially for the more extreme scenarios. Thus, integrating cascading effects between critical infrastructures into assessments is crucial for effective governance and resilience-building efforts.

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