CRITICAL INFRASTRUCTURE NETWORKS IN FLOOD RISK MANAGEMENT

Integration of Flood Risk Analysis Methods for Networks, Consideration of Network-Specific Measures and Challenges for Data Availability

Von der Fakultät für Bauingenieurwesen der Rheinisch-Westfälischen Technischen Hochschule Aachen zur Erlangung des akademischen Grades eines Doktors der Ingenieurwissenschaften genehmigte Dissertation

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Tag der mündlichen Prüfung: 4. Juli 2025

Abstract

Critical infrastructure (CI) networks are vital for the survival and functionality of society and economy. In an environment with a changing climate and more extreme weather events, it is pivotal to prepare infrastructure for these changes. Flooding, one of the major natural hazards that societies are exposed to, is addressed by constantly evolving flood risk management (FRM). However, disruptions to CI services and the cascading effects of these disruptions are not currently included in FRM. In flood risk analysis, it is state-of-the-art to determine the direct consequences of flooding on assets and people. Disrupted CI services and their networks, as well as the cascading effects propagating flood disruptions are not considered explicitly, and methods to derive these consequences are scarce. To address these challenges, a cumulative dissertation consisting of four manuscripts was prepared.

The research presented in the first manuscript of this dissertation incorporated CI into every facet of FRM, encompassing flood risk analysis, risk reduction as well as risk communication and participation. Utilising a CI network modelling technique, this approach facilitates the quantification of flood consequences for the CI within flood risk analysis. Consequently, the total flood risk, as a combination of hydrological probabilities and associated consequences, is complemented by CI consequences. The integration of CI and its network characteristics allows for enhanced decision-making in risk management. More-over, the ongoing involvement of CI operators has proven to be advantageous throughout all FRM stages. A case study conducted in Accra, Ghana, including the participatory engagement of CI stakeholders, underlines the previously mentioned findings and the continuous integration of CI into FRM.

The flood risk analysis, as a component of FRM, relies on the consideration of consequences specific to CI networks; therefore, a modelling approach of CI networks is designed. The modelling approach was conceptualised and implemented to balance simplicity and accuracy to represent the complexity of CI. In the second manuscript, catchment-wide flood risk analyses utilising a topology-based modelling approach for CI networks are proposed. The fundamental elements of the model encompass points, connectors, and polygons, which are employed to depict the layers and multi-sectorality of the CI network. This newly formulated approach was technically integrated as a CI network module into the PROMAIDES (Protection Measures against Inundation Decision support) framework for more integrated flood risk management. This method quantifies the consequences of supplying the number of affected CI users in combination with the duration of disruption. A proof-of-concept of this modelling approach was conducted in the case study area of Accra, Ghana.

FRM requires the consideration of risk management measures by definition and, in the context of this work, must account for measures within the CI domain. Many CI operators have valuable experience in managing flood risk within their sectors, offering insights into potentially effective flood risk reduction measures. The third manuscript presented in this dissertation conducts structured interviews with CI operators in Central Europe supplemented by a preparatory and follow-up literature review. The findings from the combined literature review and expert interviews were compiled into a comprehensive catalogue detailing flood risk reduction measures tailored to five CI sectors as well as a generalised measure category. A case study in Western Germany is introduced, illustrating the integration of five CI-specific flood measures from the catalogue into the flood risk analysis and management framework.

A persistent challenge across CI network modelling approaches is the lack of high-quality input and validation data. Consequently, modellers often resort to assumptions or extrapolations that introduce uncertainties that undermine model reliability. To address this challenge a generic modelling workflow is proposed in the fourth manuscript, and the data requirements for each stage are systematically defined, with a review of potential sources to enhance data collection and awareness of pitfalls. Case studies illustrate then the application of this workflow across different modelling purposes, emphasising the need to explore the implications of data scarcity and improve the reliability of the CI network model.

This dissertation advances the enhancement of critical infrastructure resilience during flood events. For the first time, it demonstrates that integrating critical infrastructure into flood risk management is not only feasible but has been successfully achieved. Special attention is given to the analysis of flood risk for CI networks because of the individual composition of these networks, as well as to the cascading effects that propagate failure due to flooding through the CI networks to other elements and sectors. Next, it is concluded that CI-specific measures are necessary, as collected in a CI-specific flood risk reduction measure catalogue. Estimating CI consequences for decision-making hinges on solid data inputs and can suffer when these inputs are scarce. However, it has been shown that raising awareness of the necessary requirements, engaging CI stakeholders, and ensuring proper distribution can overcome this shortfall.

Kurzfassung

Kritische Infrastruktur (KRITIS) und deren Netzwerke sind für das Überleben und die Funktionalität von Gesellschaft und Wirtschaft unerlässlich. In einer Umgebung mit einem sich ändernden Klima, zunehmend extremeren Wetterereignissen und komplexer werdenden Versorgungssystemen ist es entscheidend, Infrastrukturen auf diese Veränderungen vorzubereiten. Hochwasser, als eine der relevantesten Naturgefahren, denen Gesellschaften ausgesetzt sind, wird mit einem sich ständig weiterentwickelnden Hochwasserrisikomanagement (HWRM) begegnet. Disruptionen der KRITIS-Dienste und die kaskadierenden Effekte dieser Disruptionen sind derzeit nicht im ganzheitlichen HWRM berücksichtigt. Methoden zur Betrachtung von Hochwasserkonsequenzen für KRITIS sind knapp und die Berücksichtigung der indirekten und kaskadierenden Konsequenzen eine Herausforderung. Diese Dissertation untersucht die Herausforderung, die Resilienz kritischer Infrastrukturen (KRITIS) im Hochwasserfall zu verbessern, anhand von vier wissenschaftlich veröffentlichten Manuskripten.

Im ersten Manuskript dieser Dissertation wurde ein Konzept entwickelt KRITIS in die einzelnen Schritte des HWRM einzubringen. Die Verwendung einer KRITIS-Netzwerkmodellierungstechnik ermöglicht hierbei die Quantifizierung von Hochwasserfolgen für KRITIS-Netzwerke innerhalb der Hochwasserrisikoanalyse. Das Gesamthochwasserrisiko, als Kombination aus hydrologischen Wahrscheinlichkeiten und den damit verbundenen Konsequenzen, wurde dadurch um die Konsequenzen für KRITIS erweitert. Die Integration von KRITIS und ihren Netzwerkeigenschaften ermöglicht eine verbesserte Entscheidungsfindung. Die kontinuierliche Beteiligung von KRITIS-Betreibern wurde als vorteilhaft in allen HWRM-Schritten erwiesen. Eine Fallstudie in Accra, Ghana, mit partizipativem Einbezug von KRITIS-Stakeholdern wurde genutzt um das Konzept in einer Anwendung erfolgreich zu testen.

Die Hochwasserrisikoanalyse, als Bestandteil des HWRM, basiert auf der Berücksichtigung von Konsequenzen, die spezifisch für KRITIS-Netzwerke sind. Als Grundlage für die Einbeziehung von Hochwasserkonsequenzen von KRITIS-Netzwerken ist im zweiten Manuskript ein Modellierungsansatz konzipiert worden. Dafür wurden die mögliche Detailschärfe und die Fähigkeit Komplexität von KRITIS darzustellen abgewogen und in einem KRITIS Modellierungsansatz vereint. Es wurde ein topologie-basierter Modellierungsansatzes von KRITIS-Netzwerken entwickelt. Die definierten Elemente des Modellansatz umfassen Punkte, Konnektoren und Polygone, die verwendet werden, um Ebenenstrukturen und die Multi-Sektoralität des KRITIS-Netzwerks darzustellen. Dieser neu formulierte Ansatz wurde als KRITIS-Netzwerkmodul in die Hochwasserrisikoanalyse- und -management- Anwendung PROMAIDES integriert. Die Methode quantifiziert die Folgen, als Anzahl der betroffenen KRITIS-Benutzer sowie die Dauer der Disruption. Ein Konzeptnachweis dieses Modellierungsansatzes wurde im Untersuchungsgebiet von Accra, Ghana, durchgeführt.

KRITIS-Betreiber verfügen über Erfahrungen im HWRM in ihren Sektoren und können potenziell wirksame Hochwasserrisikominderungsmaßnahmen identifizieren. Im dritten Manuskript dieser Dissertation wurden strukturierte Interviews mit KRITIS-Betreibern in Mitteleuropa durchgeführt und durch eine voranstehende und nachfolgende Literaturrecherche eingerahmt. Die Ergebnisse wurden in einem Maßnahmen-Katalog zusammengefasst, der Hochwasserrisikominderungsmaßnahmen für fünf KRITIS-Sektoren sowie eine verallgemeinerte Maßnahmenkategorie umfasst. Eine Fallstudie im Einzugsgebiet der Vicht im Westen Deutschlands wurde vorgestellt, die die Integration von fünf Maßnahmen aus dem Katalog in die Analyse und damit dem HWRM des Untersuchungsgebiet testet.

Eine stetige Herausforderung für KRITIS Modellierungsansätzen ist der Mangel an hochwertigen Eingangs- und Validierungsdaten. Infolgedessen greifen Modellierende oft auf Annahmen oder Extrapolationen zurück, was Ungenauigkeiten verstärkt, die die Modellzuverlässigkeit und dessen Aussagekraft verringert. Zur Bewältigung dieser Herausforderung wurde in einem vierten Manuskript ein generischer Modellierungsprozess definiert und die Datenanforderungen für jede Phase dieses Prozess ausformuliert. Potenzielle Datenquellen wurden identifiziert und mögliche Auswirkungen durch fehlende oder ungenaue Daten wurden anhand von Fallstudien herausgearbeitet. Diese Arbeit betont die Notwendigkeit, die Auswirkungen von Datenknappheit zu erkunden und die Zuverlässigkeit von KRITIS-Netzwerkmodellen zu verbessern, um die Vorteile dieser Methoden in Zukunft greifbarer zu machen.

Die Schlussfolgerung der Dissertation zeigt, dass die entwickelten Lösungen die Resilienz von KRITIS während Hochwasserereignissen verbessern kann. Die Integration von KRITIS in ein ganzheitlicheres HWRM wurde erfolgreich belegt. Besondere Aufmerksamkeit wird der Analyse des Hochwasserrisikos für KRITIS-Netzwerke aufgrund der individuellen Zusammensetzung dieser Netzwerke sowie der kaskadierenden Effekte gewidmet. Darüber hinaus wird festgestellt, dass die Sammlung und Berücksichtigung spezifischer KRITIS-Maßnahmen für ein erweitertes HWRM notwendig ist. Die Integration von KRITIS in das HWRM kann durch die Verfügbarkeit und Qualität der Eingangsdaten noch stark negativ beeinflusst werden. Diese Datenknappheit kann jedoch durch ein erhöhtes Bewusstsein für Datenanforderungen, die Einbeziehung von KRITIS-Stakeholdern und eine angemessenes Teilen von bestehenden Datensätzen überwunden werden.

Declaration of Personal Contribution

This cumulative dissertation was prepared during my employment as a research associate in the Flood Risk Management workgroup at the University of Applied Science Magdeburg-Stendal (HS-M), Germany. The present work is elaborated for the doctorate at the Faculty of Civil Engineering at the Rhenish-Westphalian Technical University (RWTH), Aachen University, Germany, and under the acknowledgement and adherence to the principles of good scientific practice at the RWTH. The dissertation is compiled from four peer-reviewed scientific manuscripts published in international journals complying with the faculty's regulations for cumulative doctoral theses. Univ.-Prof. Dr.-Ing. Holger Schüttrumpf, chair of the Institute of Hydraulic Engineering and Water Resources Management (IWW), RWTH Aachen University, Germany, is the first member of this dissertations committee. Univ.-Prof. Dr. Stefan Greiving from TU Dortmund University, Germany, head of the Institute of Regional Planning and Risk Management is the second member of the committee. Prof. Dr.-Ing. Daniel Bachmann of the Magdeburg-Stendal University of Applied Sciences, Germany, is the content supervisor of this work and the third member of the committee.

The work presented in this dissertation is prepared in the context of the PARADeS project 'Participatory Assessment of Flood Disaster Prevention and Development of an Adapted Coping Strategy in Ghana' (Grant number 13N15273) funded by the German Federal Ministry of Education and Research (BMBF). PARADeS is a joint project led by Prof. Dr. Mariele Evers from the Department of Geography, University of Bonn, Germany, and was initiated within the framework of the International Disaster and Risk Management Project (IKARIM).

The content of this thesis is my original work, unless otherwise noted, through acknowledgements or references. During the preparation of this dissertation, I used GPT-3.5 from OpenAI and Paperpal to rephrase specific statements. After using these tools, I reviewed and edited the content as needed and take full responsibility. My contributions to the published manuscripts, listed in chronological order of publication date, are as follows.

1. Schotten, R., & Bachmann, D. (2023b). Integrating Critical Infrastructure Networks into Flood Risk Management. *Sustainability*, *15*(6), Article 6. doi: 10.3390/su15065475

This manuscript is presented in Section 2. The work conducted for this manuscript is my own and was prepared with advice and feedback from Daniel Bachmann. Critical infrastructure stakeholder participation, information and data gathering, and model generation were done by me. I wrote the original draft, created figures and tables, and implemented the suggestions and comments of the reviewers.

2. Schotten, R., & Bachmann, D. (2023a). Critical infrastructure network modelling for flood risk analyses: Approach and proof of concept in Accra, Ghana. *Journal of Flood Risk Management*. doi: 10.1111/jfr3.12913

This manuscript is presented in Section 3. The work conducted for this manuscript is my own and was prepared with advice and feedback from Daniel Bachmann. The critical infrastructure modelling method was designed and implemented in collaboration with Daniel Bachmann. The information and data gathering, as well as the model generation of the presented case study, were performed by me. I wrote the original draft, created figures and tables, and implemented the suggestions and comments of the reviewers.

3. Schotten, R., Mühlhofer, E., Chatzistefanou, G., Bachmann, D., Chen, A., & Koks, E. (2024). Data for critical infrastructure network modelling of natural hazard impacts: Needs and influence on model characteristics. *Resilient Cities and Structures*, *3*, 55–65. doi: 10.1016/j.rcns.2024.01.002

This manuscript is presented in Section 5. During the EGU conference and the Venice International University Summer School on critical infrastructure, contacts were established with other critical infrastructure experts. Based on these professional networking encounters, I organised group discussions and helped identify common interests and challenges. I identified, gathered, and moderated the group of contributors to collaborate in the joint manuscript. I wrote the original draft and created figures and tables together with Evelyn Mühlhofer and Georgios-Alexandros Chatzistefanou. The work conducted is prepared with advice and feedback from Daniel Bachmann, Elco Koks and Albert Chen. I have implemented the suggestions and comments from the reviewers.

4. Schotten, R., & Bachmann, D. (2024). Cataloguing and Testing Flood Risk Management Measures to Increase the Resilience of Critical Infrastructure Networks. Smart Cities 2024, 7(5), 2995-3021; doi: 10.3390/smartcities7050117

This manuscript is presented in Section 4. The work conducted for this manuscript is my own and was prepared with advice and feedback from Daniel Bachmann. Semi-structured interviews were conducted and analysed by me, including information and data gathering, as well as the model generation of the presented case study. I wrote the original draft and created figures and tables.

I have contributed further (non-peer-reviewed and peer-reviewed) manuscripts during my engagement as a research associate at the HS-M. These manuscripts are not further considered in this thesis, but are assembled in a list of publications at the end of this thesis.

Contents

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List of Abbreviations

Abbreviation	**Description**
1D	One-dimensional
2D	Two-dimensional
BBK	German Federal Office of Civil Protection and Disaster Assistance (Bundesamt für Katastrophenschutz und Bevölkerungshilfe)
BMBF	German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung)
CI	Critical infrastructure
CIN	Critical infrastructure network
CMWS	Community managed small town water systems
DRR	Disaster risk reduction
EU	European Union
FRA	Flood risk analysis
FRM	Flood risk management
GIS	Geo information system
HS-M	University of Applied Science Magdeburg - Stendal (Fachhochschule Magdeburg – Stendal)
ICT	Information and communication technology
IKARIM	International Disaster and Risk Management (Internationales Katastrophen- und Risikomanagement)
IWW	Institute of Hydraulic Engineering and Water Resources Management (Institut für Wasserbau und Wasserwirtschaft)
NADMO	Ghanaian National Disaster Management Organisation
NRU	Network replacement units

PARADeS	Participatory Assessment of Flood Disaster Prevention and Development of an Adapted Coping Strategy in Ghana (Partizipative Bewertung der Hochwasserkatastrophenprävention und Entwicklung einer angepassten Bewältigungsstrategie in Ghana)
PGA	Peak ground acceleration
ProMaIDes	Protection Measures against Inundation Decision support
RWTH	Rhenish-Westphalian Technical University (Rheinisch-Westfälische Technische Hochschule)
SSIP	Small-scale independent providers
UN	United Nations
WRC	Water Resources Commission Ghana

List of Symbols

Symbol	**Unit**	**Description**
A	[Number of incoming connector elements]	Authority value
C (Chapter 2 – Paper II) /P (Chapter 3 – Paper I) /CPV (Chapter 4 – Paper IV)	[Number of CI elements]	Cascade potential value
C	[USD] or [people]	Classic flood consequences
H	[Number of outgoing connector elements]	Hub value
P	[Number of disrupted people]	Disrupted population
p_{hyd}	[1/a]	Probability of occurrence
m	[Number of elements per cascade]	-
R_{CI}	[people · d / a]	Risk of population time CI disruption
t	[d]	Disruption time of CI services
T_{Pop}	[people · d]	Population time
V	[Number of CI elements]	Cascade vulnerability value
w	[-]	Value determining the weight of an CI element for a cascade

1 INTRODUCTION

This chapter introduces the connection between critical infrastructure and flooding, as considered in this dissertation. The relevance of these two topics is highlighted through a compilation of past flood events. Subsequently, a brief elaboration of the theoretical background is provided to understand critical infrastructure and flood risk management. Next, an outline of the thesis is provided to give an impression of the overall concept and the interconnections among the included manuscripts. The main research objective is then defined such as the research questions guiding each individual manuscript. The introduction concludes by elaborating on the chosen format of this cumulative dissertation.

1.1 Motivation and Relevance

The number of people at risk from flooding estimated around 1.82 billion in 2022 and climate change as well as socio economic factors are expected to increase this number significantly in the future according to the World Bank (Rentschler et al., 2022). Wherever flood events occur, impacts on infrastructure are frequently reported. Flooding impacts the closely webbed infrastructure that keeps a modern society functional (Ferguson, 2021). Viewing the meanings of infrastructure and flooding in a closer common context is clarified by looking at past flood events in Germany, for example fluvial flooding along the Elbe (2002, 2013). Moreover, flooding in Western Europe (2021) had a significant impact on Germany, Netherlands and Belgium (Lehmkuhl et al. 2022). Numerous infrastructure assets suffered severe damage or total destruction as highlighted by Koks et al. (2022) and Wolf et al. (2024). Koks et al. (2015) have shown that direct consequences such as damages to houses as well as infrastructure are exceeded by indirect economic damages for extreme events. Indirect consequences include economic or social activities, as well as critical infrastructure (CI) services. Another study by Thieken et al. (2016) has revealed that flood-affected residents experience a large range of impacts. Surveys have indicated that mental health and essential service supply issues, such as lack of electricity and access to drinking water, are perceived as more severe than financial losses. Both studies underline the relevance of investigating CIs in the context of flooding events.

Considering future trends, this relevance may even increase. Fekete and Sandholz (2021) underline the growing vulnerability of German society to disruptions in their examination of the 2021 floods, attributed to a heightened dependency on its infrastructure. In other income areas, the level of dependency may differ significantly. During the analysis of flooding caused by Storm Daniel in the Mediterranean Sea (2023), Qiu et al. (2023) highlighted that the maintenance of infrastructure is especially challenging for low-income areas because normal conditions are already a challenge compared to high-income areas such as Germany. The analysis of infrastructure thus requires highly individual approaches that consider the level of technical dependency as well as social factors.

The legislative also acknowledges the need to better understand the resilience of infrastructure. At the end of 2022, the Critical Entities Resilience Directive was adopted (European Parliament & Council of the European Union, 2022) which is required to become a national law by 2024, as proposed by the German Federal Ministry of the Interior and Community, with a draft for the critical infrastructure framework law (KRITIS Dachgesetz) (Atug, 2023). The draft proposes, among other things, to make resilience requirements for natural hazards, such as flooding, mandatory for operators of CI (KRITIS) starting in 2024, and also calls for con-sideration of dependencies among these CI operators before investing in potential measures.

Investment in adaptation measures to overcome challenges due to flooding may be beneficial for all countries, irrespective of whether they live in high- or low-income areas (Winsemius et al., 2016). Developing a method to steer the development of flood risk reduction measures is relevant in an environment with a changing climate and society that increases its dependency on technical infrastructure.

1.2 Theoretical Background and Knowledge Gaps

CIs are defined by the services and goods they provide and that are essential for societal functions, health, safety, security or the economic and social well-being of people (Liu & Song, 2020). Institutions define the boundaries of their responsibility for CI, for example, based on the number of connected end-users, as exemplified by the BBK, which considers critical infrastructure as serving over 500 000 end-users (Federal Office of Civil Protection and Disaster Assistance – BBK, 2022). In addition to their services, CI is also defined by its organisation into sectors that are interdependent, forming a critical infrastructure network (CIN) (Rinaldi et al., 2001). The CER Directive identifies critical entities by evaluating the significance of a disruptive effect in case of failure, considering key criteria such as: number of dependent users, cross-sectoral reliance and cascading effects, degree and duration of societal and economic consequences, market dominance of the entity, geographic reach, and the availability of alternative services (European Parliament & Council of the European Union, 2022). The definition of critical entities is more supply- and end-user oriented, focusing on the essential services they provide, whereas critical infrastructures are inherently asset- and element-driven, centred on the physical or digital systems themselves. In Germany, as defined by the BBK, critical infrastructures are organized into key sectors such as energy, information technology and telecommunications, transport and traffic, and health amongst others; these sectors further encompass subsectors, for example, electricity, internet exchange points, public transport, and hospitals. Therefore, it is noted that the definitions of critical entities, critical infrastructures or structures providing critical services, vary in the context of their regional application. The sector definition used in this study differentiates energy, water, nutrition, information and communication technology (ICT), health, and transportation. The arrangement of CI sectors in a network with dependencies causes disruption in one sector to progress within a sector (sectoral) or across sectors (transsectoral), and disrupts other CI (Ouyang, 2014). These cascading effects must be considered when investigating CI and flooding (Fekete, 2019a; Serre & Heinzlef, 2018). Figure 1-1 visualises a schematic network with point elements from three sectors (electricity, water supply and ICT). It is shown how a disruption affecting one electricity infrastructure cascades through dependencies of the simplified network model to residential areas causing service disruptions there.

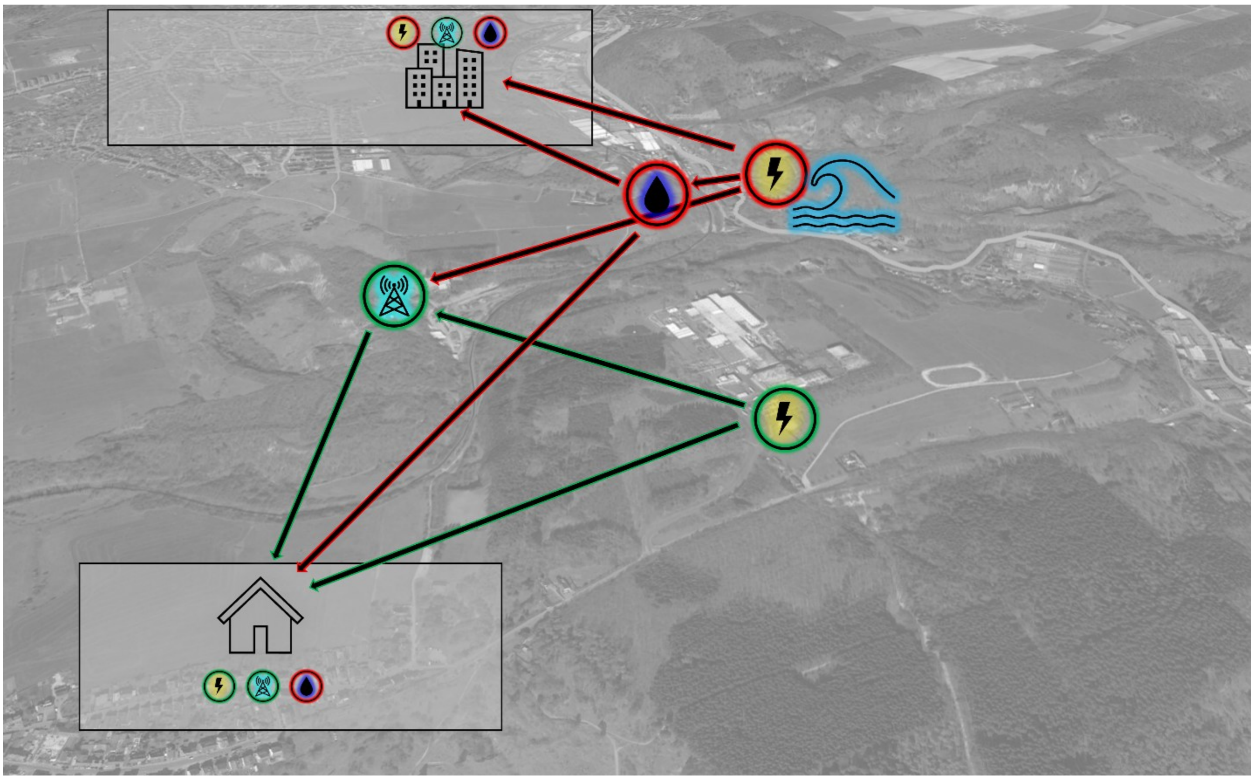


Figure 1-1: Simplified network model consisting of point, polygon and connector elements. Red elements are disrupted and green elements still functional.

Integrated flood risk management (FRM) is achieved based on flood risk analysis (FRA), assessment, and communication. Figure 1-2 summarises FRM as state-of-the-art and includes the major points of the EU Flood Directive (European Parliament & Council of the European Union, 2007). The Floods Directive bases its assessment and management of flood risks on spatial exposure to flooding, combined with probabilities and vulnerabilities. This approach is also referred to as a "place-based approach” as invoked in German national law by the Regulation on Federal Spatial Planning for Cross-State Flood Protection (German Federal Ministry of the Interior and Community – BMI, 2021). In the legal context, the Floods Directive and the CER Directive complement each other: The Floods Directive adopts a spatial approach to flood risk assessment, while the CER Directive focuses on a systemic risk management approach for critical infrastructure. FRA combines the probability and consequences of flooding, where the consequences are a combination of vulnerability and exposure (Klijn et al., 2015). Flooding can be classified as fluvial, pluvial, coastal, or groundwater flooding, and a combination of these can be considered (Becker et al., 2022; Davlasheridze et al., 2019; Hofmann & Schüttrumpf, 2019; Kreibich et al., 2015). Some research has also proposed not seeing flooding as an isolated hazard but considering a multi-hazard aspect because one natural extreme is usually accompanied by other hazards (de Ruiter, 2020; Gentile et al., 2022). Flooding can occur in combination with drought, landslides, wildfires, and earthquakes. The derivation of flood maps for FRA is based on different approaches which can vary from empirical, physical, or data-driven techniques, or a combination of the previously mentioned (Gebremedhin et al., 2020; Hofmann & Schüttrumpf, 2021; Leijnse et al., 2022).

The consequences of flooding considered in FRA are as diverse as the societies they affect (cf. Figure 1-2). Flood consequences can be categorised as direct, indirect, tangible, and intangible, as proposed by Merz (2006). Direct flood consequences result from direct contact with floodwaters, while indirect consequences occur independently of water contact or extend beyond the flood's area and duration. Tangible consequences are quantifiable in monetary terms, whereas intangible consequences such as loss of cultural values cannot be effectively represented by monetary values.

Direct, tangible flood consequences have been investigated intensively for several years among others by Delalay et al. (2020), Huizinga et al. (2017) and Wagenaar et al. (2018). Direct, intangible flood consequences are progressing further towards state-of-the-art art as well as an integral part of FRA (Bachmann & Schüttrumpf, 2014; Jonkman, 2007; Jüpner et al., 2018). The indirect and tangible, and intangible consequences of flooding still receive minor awareness, such as mental health (Dassanayake, 2022) or the relevance of CI services (Kuhlicke et al., 2021).

The flood risk is managed and based on the FRA, the flood risk situation is assessed, and it is decided whether acceptance leads to the management of residual risk or denial triggers the consideration of flood-risk-reducing measures (cf. Figure 1-2). Decision-making for acceptance or denial has been widely investigated (Altarawneh et al., 2016; Buchecker et al., 2013). This step in the active management of flood risk has to be done under the consideration of communicating with multiple stakeholders throughout the whole process, preferably already during the analysis (De Brito & Evers, 2016). After the decision stage and based on acceptance or denial of the flood risk situation, a range of flood risk reduction measures are available at the household and building level (Attems et al., 2020; Meyer & Hartmann, 2023) but also on a wider scale, such as the catchment or regional level (Dittrich et al., 2019; Wagenaar et al., 2019). Examples for catchment-wide measures can be re-forestation, dams, dikes, protection walls or retention ponds (Bachmann & Schüttrumpf, 2014). These potential measures are included in the FRA to validate the potential for reducing flood risk. The implementation of measures concludes the FRM procedure.

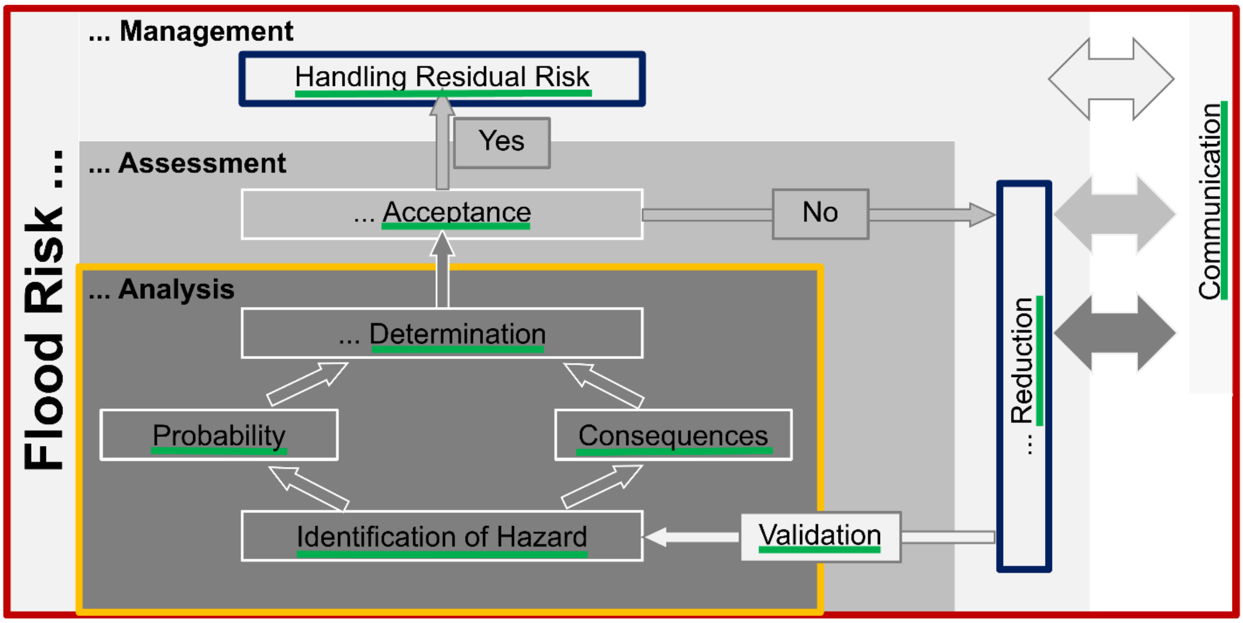
> *The overarching knowledge gap addressed in this dissertation is the integrated consideration of critical infrastructures in flood risk management.*

Currently, there is an absence of established modelling approaches that transcend place-based risk management, address systemic risks, or integrate the significance criteria outlined in the CER Directive. This includes for example the consideration of the number of dependent CI users, cross-sectoral reliance as well as cascading effects. Only fragments of FRM are addressed or required to consider CIs. The European Union's Critical Entities Resilience (CER) directive draft approaches CI but not flooding specifically, and the European Union's Flood Directive addresses flooding but not CI; FRM for CI specifically remains unaddressed. Another aspect of the CER Directive requires CI operators to consider cascading effects but fails to propose how these cascading effects should be identified. This exposes an existing gap in methods for systematically deriving CI dependencies. In line with the previous point, Vorogushyn et al. (2018) have called for the integration of indirect flood consequences beyond the flooded area owing to the failure of CIs in FRA. De Brito & Evers (2016) have endorsed the active participation of all stakeholders, including CI operators and users, in all the steps of decision-making in FRM. To conclude the recommendations for the FRM process, it has been shown in a literature review by Ani et al. (2019) that the methods lack the identification of potential measures. In FRM the component of FRA has shown few examples of considering the consequences for critical infrastructure networks. Additionally, a gap is identified to include potential measures and their effects in the combination of CI and FRM.

1.3 Thesis Outline

The presented dissertation thesis is cumulative and consists of four individual manuscripts that address aspects of the previously identified knowledge gaps (cf. Chapter 2, 3, 4, 5). Figure 1-2 illustrates the manuscripts' delineation of an integrated approach for incorporating CI into FRM. The specific focus of each manuscript is represented by distinct colours in Figure 1-2. The foundation of this work describes the overall concept of integrating CI into FRM in Chapter 2. Chapter 3 focuses on FRA and the definition of a modelling approach to consider the consequences on CIN. In Chapter 4, a manuscript that describes the systemic collection of flood management measures for CIs from stakeholder interviews is presented. The last chapter concentrates on the role of data availability as well as performance for CIN impact modelling for natural hazard impacts in general, and was collaboratively prepared by a group of CIN experts to gather collective insights and experiences (cf. Chapter 5). In the synthesis, the research objectives are revisited, and the results are presented, challenges and limitations are briefly discussed, and future research objectives and potentials are formulated.

1.4 Research Objective and Research Questions



1. Schotten, R., & Bachmann, D. (2023b). Integrating Critical Infrastructure Networks into Flood Risk Management. *Sustainability*, *15*(6), Article 6. DOI: /10.3390/su15065475
2. Schotten, R., & Bachmann, D. (2023a). Critical infrastructure network modelling for flood risk analyses: Approach and proof of concept in Accra, Ghana. *Journal of Flood Risk Management* 16(3), DOI: 10.1111/jfr3.12913
3. Schotten, R., & Bachmann, D. (2024). Cataloguing and Testing Flood Risk Management Measures to Increase the Resilience of Critical Infrastructure Networks . *Smart Cities* 7(5), 2995-3021, DOI: 10.3390/smartcities7050117
4. Schotten, R., Mühlhofer, E., Chatzistefanou, G., Bachmann, D., Chen, A., & Koks, E. (2024). Data for critical infrastructure network modelling of natural hazard impacts: Needs and influence on model characteristics. *Resilient Cities and Structures*, *3*, 55–65. DOI: 10.1016/j.rcns.2024.01.002

Figure 1-2: Arrangement of individual publications into a coherent framework of flood risk management.

Based on the relevance of the presented topic and the identified knowledge gap an overall research objective of this work can be defined.

The overall objective of this dissertation is to enhance the resilience of critical infrastructure networks during flood events, ensuring more continuous service provision.

The previously introduced manuscripts elaborate on different aspects of the overall research objective. A set of research questions further defines how the individual manuscripts contribute to addressing this objective. The manuscripts, their respective research questions, and the methodological approaches used to address these questions and the overall objective are introduced in the following subsections.

1.a) What is the state-of-the-science with regard to the integration of CI into the individual steps of FRM?

1. Schotten, R., & Bachmann, D. (2023b). Integrating Critical Infrastructure Networks into Flood Risk Management. *Sustainability*, *15*(6), Article 6. DOI: 10.3390/su15065475

1.b) How can a comprehensive approach be shaped to incorporate CI into each step of the FRM?

1.c) Can the proposed approach be proven to improve FRM in a case study?

The reply to the first research question is as follows: 1.a) was answered with a literature review collecting state-of-the-science literature on FRM, as well as its individual steps that consider CI. For the second research question, 1.b) the FRM process was defined by assembling previously identified research findings and new approaches. Additionally, a new management approach was developed with special consideration of CI. For the third research question 1.c) a proof-of-concept is presented that demonstrates the application of the proposed method in the city of Accra, Ghana.

2. Schotten, R., & Bachmann, D. (2023a). Critical infrastructure network modelling for flood risk analyses: Approach and proof of concept in Accra, Ghana. *Journal of Flood Risk Management*. DOI: 10.1111/jfr3.12913

2.a) What are the most effective approaches for modelling the functionality and service of CIN?

2.b) Which modelling approach for CIN is suitable for flood risk analysis in FRM?

2.c) How can this modelling approach be applied in flood risk analysis?

A literature review is presented to show the modelling approaches that are available. It categorises the possible functionalities and services that are represented to answer research question 2.a). Research question 2.b) is addressed by defining the input data, modelling approach, and output data tailored specifically to the needs of FRM. The third question, 2.c), is answered with a FRA in Accra Ghana under consideration of CI and points out the benefits of this addition.

3. Schotten, R., & Bachmann, D. (2024). Cataloguing and Testing Flood Risk Management Measures to Increase the Resilience of Critical Infrastructure Networks . *Smart Cities* 7(5), 2995-3021; DOI: 10.3390/smartcities7050117

3.a) Which flood risk reduction measures can be considered for different CI sectors?

3.b) How can a collection of flood measures tailored to CI support the integration of CI into FRM?

Research question 3.a) was investigated by combining structured CI expert interviews with a preliminary and follow-up literature review. The findings of this investigation are processed into a flood-risk-reducing measure catalogue categorised by CI sectors and steps of the disaster risk management cycle. The value of this catalogue was subsequently demonstrated in a proof-of-concept along the Vicht river in Germany to address research question 3.b).

4. Schotten, R., Mühlhofer, E., Chatzistefanou, G., Bachmann, D., Chen, A., & Koks, E. (2024). Data for critical infrastructure network modelling of natural hazard impacts: Needs and influence on model characteristics. *Resilient Cities and Structures*, *3*, 55–65. DOI: 10.1016/j.rcns.2024.01.002

4.a) What data requirements are necessary for risk modellers to analyse the consequences of natural hazards in general?

4.b) How can data scarcity be effectively addressed and mitigated?

4.c) What are the implications and potential impacts of data scarcity on the analysis process and outcomes?

First research question 4.a) is approached by defining a generalised modelling workflow for the analysis of the natural hazard consequences of CI. Research question 4.b) is addressed by collecting examples of data sources for diverse applications. The last research question 4.c) is considered by defining three typical model purposes and outlining the potential influence of data scarcity on them.

1.5 Format

This dissertation consists of four manuscripts that have been published in international journals. Each manuscript was extensively peer reviewed before acceptance, and thus, multiple reviewers shared their influence on expression and form in the manuscript. It is to be considered that the terminology changes during the preparation of the manuscripts to address individual reviewers' comments. Changes in the abbreviations in the chapters are indicated in the List of Abbreviations. The terminology of certain expressions may differ slightly in each manuscript. This especially applies to the definition of the critical infrastructure sectors and subsectors which evolve and change across the manuscripts. All manuscripts presented in the chapters remained unchanged compared to their published forms. The literature references of the four manuscripts are combined in an overall list of references and complemented by new references used in the introduction and synthesis of the overall dissertation. Only the manuscript presented in Chapter 4 has been modified from American to British English to ensure coherent language use. The manuscripts are presented not in chronological order but to in a logical order.

It is recommended that each chapter is comprehended individually. The overall concept that connects the manuscripts is presented in the introduction (cf. Chapter 1), and the synthesis (cf. Chapter 6). The interconnectedness between the manuscripts and the overarching framework of this dissertation is discernible through the observation that the outlook from one manuscript often serves as a precursor to the content of the other manuscripts.

2 INTEGRATING CRITICAL INFRASTRUCTURE NETWORKS INTO FLOOD RISK MANAGEMENT

Schotten, Roman; Bachmann, Daniel

Sustainability *2023,* 15*(6), 5475*

DOI: 10.3390/su15065475

Critical infrastructure (CI) networks are essential for the survival and functionality of society and the economy. Disruptions to CI services and the cascading effects of these disruptions are not currently included in flood risk management (FRM). The work presented in this study integrates CI into every step of FRM, including flood risk analysis, risk mitigation and risk communication. A CI network modelling technique enables the flood consequences for CI to be quantified as part of the flood risk analysis. The CI consequences derived from this analysis include spatial overviews and the temporal succession of CI disruptions. The number of affected CI end-users and the duration of the disruption are arranged in a risk matrix and in a decision-making matrix. Thus, the total flood risk is extended with CI consequences. By integrating CI and CI network characteristics into the flood risk assessment and the mitigation steps, a wider range of measures for action can be considered. Additionally, the continuous participation of CI operators is introduced as beneficial for every step of the FRM. A case study in Accra, Ghana proves the benefits of CI integration for all FRM steps. During participatory CI stakeholder engagements for this study six CI sectors were identified for the assembly of the CI network. The backbone of the analysis is a multisectoral, layered CI network model with 433 point elements, 1216 connector elements and 486 polygon elements.

2.1 Introduction

Flood events have imminent and long-term consequences for people and the economy revolving around the restoration and replacement of critical infrastructure (CI) services (CEDIM Forensic Disaster Analysis (FDA) Group et al., 2021; The New York Times, 2012). In this paper, critical infrastructure services are defined as services supplied by infrastructure that are vital for a civil society. CI is the technical structures required for supplying these services and are organised in sectors such as energy, water, information and communication technology (ICT), health, emergency services, transportation and more (Federal Office of Civil Protection and Disaster Assistance – BBK, 2022). CI networks are formed by considering the interdependencies of these individual CI sectors. A recent report from the European Commission's Joint Research Centre shows that flooding damage in the electricity sector caused by disruption exceed the repair costs. The expected damage is six till eight times greater when indirect intangible consequences outside the inundated area are considered (Georgios et al., 2019). Researchers advocate for the inclusion of indirect flood consequences caused by the failure of critical infrastructure in the flood risk analysis (Vorogushyn et al., 2018).

In Western Europe, critical infrastructure supplies such as gas and telecommunications were still dysfunctional several months after the flood event that took place in summer 2021, and the livelihood of the affected residents remained disrupted (Fekete, 2019b). These experiences have prompted researchers to call for the climate change resilience of CI to be audited more thoroughly, including with regard to flooding (Kuhlicke et al., 2021).

The work presented in this paper starts with a review of current FRM practises and CI analysis and assessment methods. After that, the individual steps of the state-of-the- art FRM approach are described with a focus on CI integration. Finally, the proposed integration of CI is demonstrated in a practical application: A case study in Accra (Ghana).

2.2 Literature Review

To tackle the current lack of focus on combining critical infrastructure resilience with strategic flood risk management, flood risk management directives can be used. These are briefly analysed below. Following the 9/11 terrorist attacks in New York, public policies started to concentrate on critical assets and infrastructure. Since then, the definition of CI has continuously evolved, from critical assets to infrastructure towards networks and, ultimately, the critical function they fulfil. The EU refers to CI as critical entities. Critical infrastructure resilience policies need to represent the impact of natural and man-made hazards as well as the dynamic of an interdependent system according to the Organisation for Economic Cooperation and Development (OECD) (OECD, 2019).

The United Nations (UN) Sendai Framework recommends action for critical infrastructure services in the areas of disaster risk reduction and flood risk management. The Sendai Framework highlights direct damage to CI as well as the disruption of CI services. Furthermore, it calls for a reduction of these two types of damage and an increased resilience by 2030 (United Nations, 2015). Additionally, the UN embeds systemic thinking in its guidance documents. It is highlighted that the impacts of climate change, among other factors, lead to a systemic risk that goes beyond conventional risk management and governance (Sillmann et al., 2022).

The European Union (EU) Flood Risk Management Directive (European Parliament & Council of the European Union, 2007) provides a framework for dealing with flood-related issues at European level. Flood hazard and flood risk maps are being developed, primarily for risk communication regarding selected water bodies. The flood hazard for three hydrological scenarios (with high, medium and low probability) is presented and communicated in flood hazard maps. The direct consequences are communicated in flood risk maps. However, this particular directive does not mention the critical supply infrastructure. Complementary to the previous directive is the EU directive on the resilience of critical entities, which was expected to be finalised at the end of 2022. This indicates a shift from a focus on the transport and electricity sectors in the previous directive of 2008 towards a Europe-wide strategic analysis of critical entities (Presidency of the European Council, 2021).

In 2021, the United States initiated the Bipartisan Infrastructure Deal, releasing an investment of USD 50 billion and highlighting the importance of maintaining infrastructure. The deal places a specific focus on adapting to climate change which, besides droughts, heat and other hazards, includes flooding (The White House, 2021). The legislation recognises the systemic role of critical infrastructure, referring to CI as “system-wide critical lifelines”, which are to be protected.

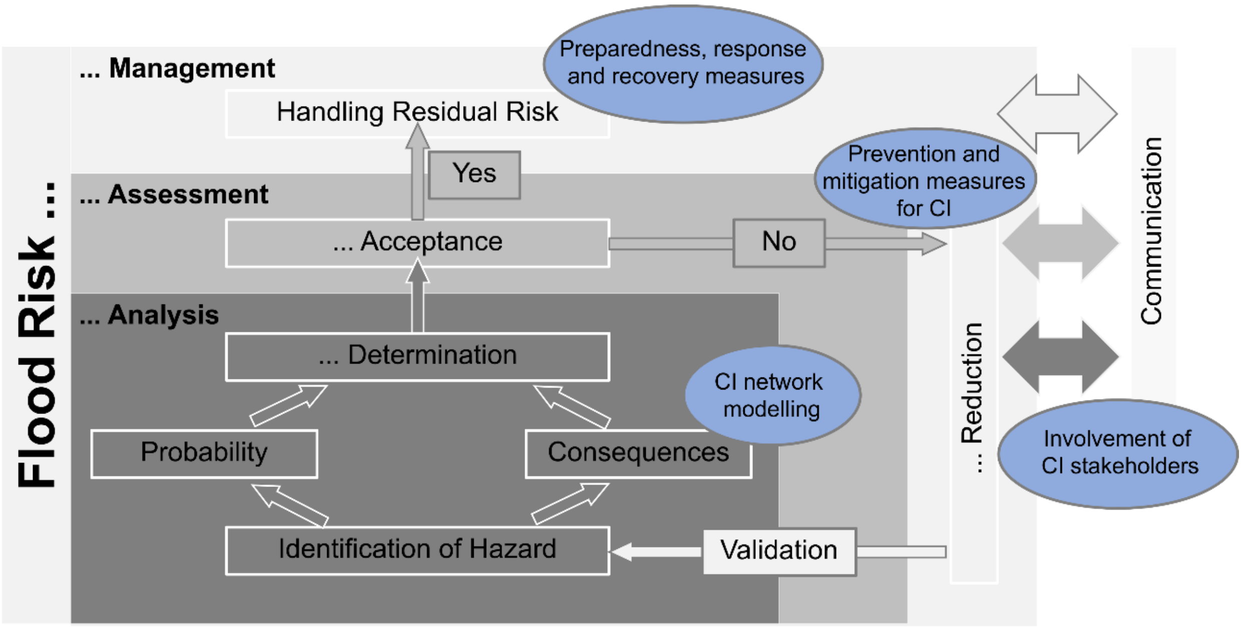


Figure 2-1: Generalised summary of flood risk management workflow, including ellipses marking the integration of CI.

Few German regulations on CI and FRM connect both topics in detail. The regulation of the cross-state spatial plan for flood protection calls for better protection of plants and facilities of national and European importance by focusing on corresponding critical and vulnerable infrastructure (German Federal Ministry of the Interior (BMI), 2011). The regulation emphasises the special systemic functionality and relevance of CIs as their failure and the subsequent cascading effects can exceed the magnitude of the directly impacted areas.

The German Federal Office of Civil Protection and Disaster Assistance (BBK) calls for integrated risk management that connects CI operators (Federal Office of Civil Protection and Disaster Assistance – BBK, 2022). The German Water Resources Act deals, among other things, with water management planning and flood protection in Germany at federal level. However, it does not mention the term critical infrastructure or the systemic functionality and criticality of its supply. Individual sectors, such as transport infrastructure, are considered isolated from each other (German Federal Ministry of Justice, 2009). In the North Rhine– Westphalia (NRW) State Water Act, critical infrastructure is only mentioned for specific sectors. A lot of attention is paid to securing the drinking water supply for facilities in flood plains through technical measures or alternative facilities. However, there is no exploration of interdependencies with other CI sectors (Ministry of the Interior of the State North Rhine Westphalia (NRW), 2022). As the directives mentioned in the previous section show, complex critical infrastructure networks are rarely included within FRM practices. A range of the state-of-the-science literature addresses the steps of flood risk management shown in Figure 2-1 individually for the topic of CI. The methods for embedding CI in flood risk directives are already available, and CI models are currently used in different management contexts already, such as supply chain management, cyber security and transportation routing (Ani et al., 2019).

CI modelling methods also diverge from each other in terms of their structure, function and purpose. Empirical approaches (Murdock et al., 2018), economic theory-based approaches (Koks et al., 2019), network-based approaches (Pant et al., 2018; Schotten & Bachmann, 2023a) and multi-sectoral approaches are four of the possible approaches towards assessing the consequences relating to critical infrastructure services and flooding. Flood risk analyses including CI are executed for a range of spatial boundaries, ranging from building level to a regional level as well as the global level (Lhomme et al., 2013; Nirandjan et al., 2022). Additionally, they can be differentiated by the CI sectors that are included in the analyses. Analyses can consider one individual sector (van Ginkel et al., 2020), one sector including dependencies on individual network elements from other sectors (Emanuelsson et al., 2014; Pant et al., 2018) or a system of CI sectors within one CI network (Pant et al., 2017).

Relevant for the work presented here is the modelling approach of Schotten and Bachmann, which focuses on flood risk modelling, including the direct and indirect consequences for a multi-sectoral CI network (Schotten & Bachmann, 2023a). Murdock et al. (Murdock et al., 2018) used the disruption of critical infrastructure services as the expected disruption for quantification.

In addition to a technical description, ongoing public and expert participation has proven to improve public and expert support for big infrastructure projects (Verein Deutscher Ingenieure, 2015). Due to the dependencies of CI sectors, methods have been developed for CI operator engagement (de Bruijn et al., 2016; de Bruijn et al., 2019; Greiving et al., 2021). One approach used as a reference for this work is the CIrcle (Critical Infrastructure: Relations and Consequences for Life and Environment) approach, which consists of preparing and executing a workshop in three major steps (Deltares, 2021): 1. stakeholder identification and involvement; 2. participatory assembly of CI network for the current risk status and future scenarios; 3. development of mitigation measures. On the one hand, international, national, and state-wide legislation considers CI for FRM only selectively. The dependencies with other sectors as well as cascading effects are not always considered. On the other hand, research methods are available with the potential to support the individual steps of FRM (Burzel et al., 2014).

2.3 Integrating Critical Infrastructure in the Steps of Flood Risk Management

The method introduced in the following chapter closes the existing gap between FRM and CI. The main purpose of this method is the integration of CI into each step of FRM. The steps of FRM are described in their current form as used in practice. In parallel, the integration of CI is defined. Universally accepted definitions of an integrated FRM include four steps: Analysis, assessment, management and communication (Bachmann & Schüttrumpf, 2014; De Brito & Evers, 2016; Klijn et al., 2015; Kobayashi & Porter, 2012; Samuels et al., 2010; Schüttrumpf et al., 2013). Figure 2-1 summarises these steps and their connections in an FRM workflow. The initial step of FRM is the analysis of the current state of an area being investigated. The assessment of the current state is then concluded based on the findings of a flood risk analysis (FRA). This results in either acceptance of the current state or denial. Acceptance triggers the question of how to deal with the residual flood risk. Denial results in the development of measures to improve the flood risk situation. The potential measures put in place are validated in a flood risk analysis of the new desired state. This whole process is accompanied by ongoing communication with stakeholders.

In this paper, these steps of FRM are elaborated on further in the beginning of the subchapters. The focus is then to describe the integration of CI in every step extensively.

2.3.1 Flood Risk Analysis of Critical Infrastructure Network

The first step of the flood risk management is the FRA, which first identifies potential hazards and then derives a range of consequences and associated probabilities. In this paper, “probability”, “hazard” and “consequences” are used as terms where the consequences are a combination of exposure and vulnerability. This paper describes catchment-based flood risk analyses based on Bachmann and Schüttrumpf (Bachmann, 2012; Bachmann & Schüttrumpf, 2014). The focus on entire river catchments ensures that hydraulic responses of potential measures up and down the river are considered.

2.3.1.1 Hazard Identification and Probability of Occurrence

For flood risk management, the hazard is inundation due to fluvial, pluvial or coastal flooding or flash floods. The key aspect is the identification of flooded areas as well as associated water depth and velocity. For the suggested integration of CI into FRM, the existing methods for hazard identification and their associated probabilities are used. Inundation maps are used to derive the water level at CI structures during flooding events. Hydrological and hydraulic modelling are the state-of-the-art tools to achieve this identification for operational and strategic flood risk analysis, from a local to a global scale (Eilander et al., 2020; Emerton et al., 2016; Khosh Bin Ghomash et al., 2022; Muis et al., 2016; Nirandjan et al., 2022).

Realistic flood risk analyses operate within the boundaries of uncertainty and therefore include the probability of the consequences, as shown in Figure 2-1. Probability is introduced by the hydrological boundaries and the determination of the associated extreme events (Winter et al., 2020). Discrete probabilities are derived from return periods of discharge or precipitation events (e.g., T10, T100 or T1000) and transformed into continuous probabilities, considering the lower and higher class boundary of every hydrological event (Bachmann, 2012). Further on in this paper, these continuous probabilities are referred to as probability of occurrence p_{hyd} [1/a].

2.3.1.2 Flood Consequences for the Critical Infrastructure Network

Integrated flood risk management requires a broad view of different types of flood consequences, as shown in Table 2-1. State-of-the-art FRA considers direct, tangible (Kreibich et al., 2017; Wagenaar et al., 2019) and direct, intangible flood consequences (Huizinga et al., 2017; Jonkman, 2007; Koks et al., 2015; Wagenaar et al., 2018). However, a wide range of flood damage consequences are not yet considered as standard in model-based consequence analysis in FRA. CI disruptions on a multisectoral level as direct and intangible consequences are added to the categorisation of flood consequences in Table 2-1. In addition, the CI service disruptions due to cascading effects are added to the category of intangible and indirect consequences. Cascading effects describe the transmission of disruptions through the dependencies of CI structures within a CI sector (sectoral) and between different CI sectors (intersectoral).

For the quantification of these cascading effects in CI networks, the modelling approach of Schotten and Bachmann is applied (Schotten & Bachmann, 2023a). In general FRA, a combination of exposure and vulnerability is used to define consequences (Klijn et al., 2015). The same applies to critical infrastructure networks. To represent CI networks exposure, three types of network elements are used in the chosen modelling approach: point elements, polygon elements and connector elements. Point elements represent CI structures and have attributes that assign them to a sector and a level in their sector (cf.

Table 2-1: Categorisation of flood consequences, including the integrated categories for CI (Schotten & Bachmann, 2022).

	Tangible (Monetary)	**Intangible (Non-Monetary)**
Direct (contact with water)	Buildings, Housholds	Affected People
	Industry and Business	Environmental Values
	Agriculture and Forestry	Cultural Values
	Infrastructure	Personal Values
	Cars	**Critical Infrastructure Services**
Indirect (No contact with water)	Business Disruptions	Loss of Trust in Region
	Traffic Disruptions	Psycho-Social Consequences
	Cost of Emergency Measures	Epidemics and State of Emergency
	Unavailability of Agricultural Land	**Cascading Effects on Critical Infrastructure Services**

Table 2-2). The threshold attribute of the point element defines the vulnerability to water depth causing a disruption. The connector elements are used to connect point elements and polygon elements. Additionally, connector elements cascade the disruption to other elements that are connected. Polygon elements define the spatial extent that their connected point elements are associated with or at least partially associated with. In addition, the polygon is defined by the number of end-users or consumers it supplies with a service. Table 2-2 summarises all the previously described attributes and others. For more information, refer to Schotten & Bachmann (2022).

Network characteristics are derived in this modelling approach to simplify the understanding of the network formed by the network elements. The cascade potential value *C*

Table 2-2: CI network elements and their associated attributes (Schotten & Bachmann, 2022).

Element	Input Attributes	Description
Point (Nodes, Vertices) ○	Point-, Sector Index	Unique identification for point; Sector specific identification.
	Sector Level	Quantitative representation in the hierarchy per sector.
	Threshold	Waterlevel threshold for which exceedance results in failure of CI structure
	Recovery Time	Time until functionality of a structure is regained
Polygon (Area) ⬠	Polygon-, Sector Index	Unique identification for polygon; Sector specific identification
	End Users	Number of users represented by polygon
Connector (Edge) ⇨	Connector Index	Unique identification for connector
	Source- , Sink Index	Source point identification or sink point/polygon identification
	Type of Source and Sink	Sector identification of source and sink element

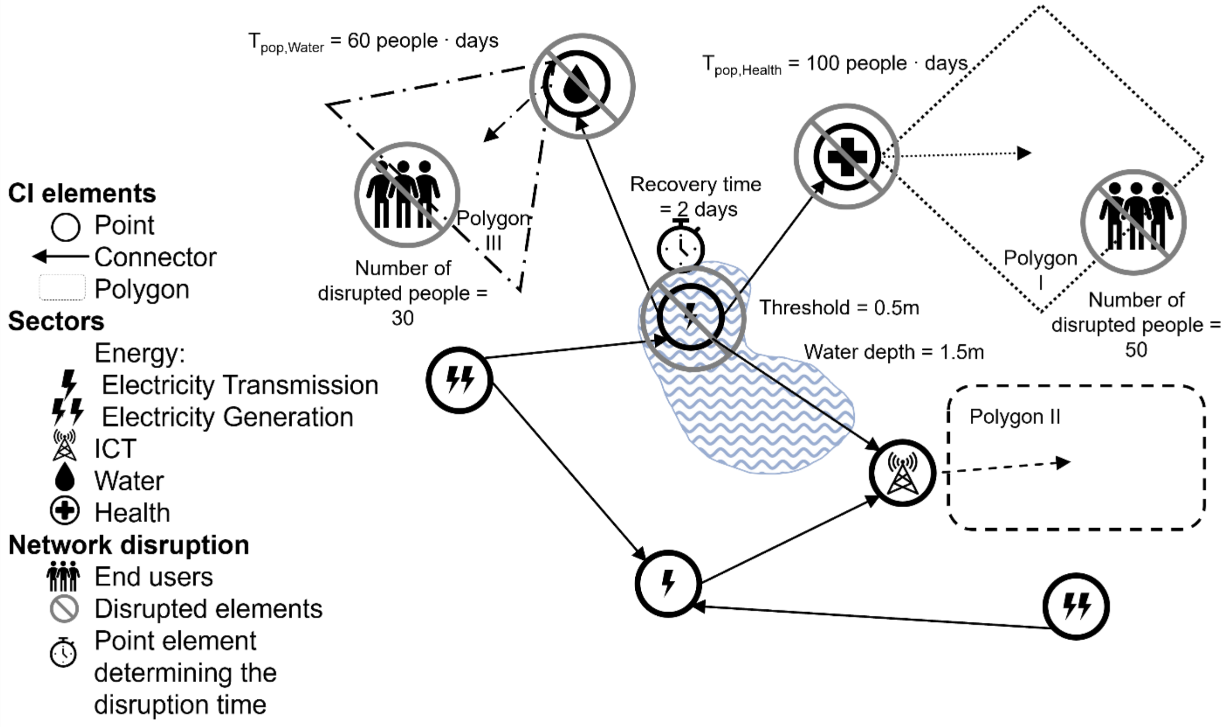


Figure 2-2: Determination of population time T_{Pop} in a representative small network impacted by a flood (Schotten & Bachmann, 2023).

describes the potential of a network element to cause a disruption in other network elements. C stands for an estimate of potentially indirectly disrupted network elements from one directly affected point element. Complementary to this, the cascade vulnerability value V describes how many network elements can disrupt the associated network element that is directly associated with end-users. V describes the vulnerability to cascading effects in a network arrangement and can highlight specific locations or sectors for further assessment. Additional sources on the derivation of other network characteristics can be found here: (Arosio et al., 2020; Schotten & Bachmann, 2023a).

Two calculation modes are available to determine the consequence for CI: (1) a steady state calculation of the CI network based on the maximum water depth in the connected hydrodynamic 2D element, and (2) an unsteady state calculation, connecting the water depth for every time step of the hydrodynamic to the point elements.

Figure 2-2 shows a basic CI network model with one inundated CI structure from the energy sector in the centre, as replicated from the calculation. From there, cascading effects transmit the disruption to two point elements in the water and health sector and subsequently their connected polygon elements. The polygon elements are associated with a number of end-users. If there is disruption, this determines the number of disrupted people per sector $P_{dis,sec}$ [people]. The recovery time of the centre element indicates the time of disruption t_{sec} [d] for the other network elements. Based on (Murdock et al., 2018; Schotten & Bachmann, 2023a) a combination of $P_{dis,sec}$ and t_{sec} of all end-user elements per sector e results in the population time per sector T_{Pop} [people · s]:

$$T_{Pop,Sec} = \sum_{i=0}^{e} P_{dis,Sec,i} \cdot t_i \qquad (2\text{-}1)$$

In addition to $P_{dis,sec}$, this modelling approach provides other insights into the consequences for CI. Spatial overviews of the disruption per sector, cascade chains and the chronological sequence of impacts are some examples.

The modelling approach is implemented as CI network module to the flood risk management software ProMaIDes. This software enables the flood risk analysis of other flood consequences categories in parallel such as affected and endangered population or economic damage (Bachmann et al., 2021). The ProMaIDes software framework is supported by a GIS (geo information) system, a PostgreSQL database and plugins for pre- and postprocessing (Bachmann, 2023). Documentation supports the model generation and analysis of the CI network modelling approach (Schotten & Bachmann, 2022b).

Data acquisition is a key challenge for the input and validation of this modelling approach. Data quality significantly impacts the CI network model's level of granularity and fidelity. Examples have shown how this information is derived in a participatory workshop setting (de Bruijn et al., 2016; Greiving et al., 2021) or through empirical sources (Koks et al., 2022; Zorn, 2017).

2.3.1.3 Determination of Risk for CI Consequences

The concept of risk as applied in this paper considers the probability of occurrence p_{hyd} in combination with the consequences for each hydrological hydraulic event C_{hyd}. Table 2-3 summarises the risk for a range of consequence types relevant for decision-makers, such as ecological damage and people affected and endangered. As well as the risk, hydraulic and hydrological boundaries need to be addressed to account for compulsory maximum or minimum discharges and the planning of retention areas, for example.

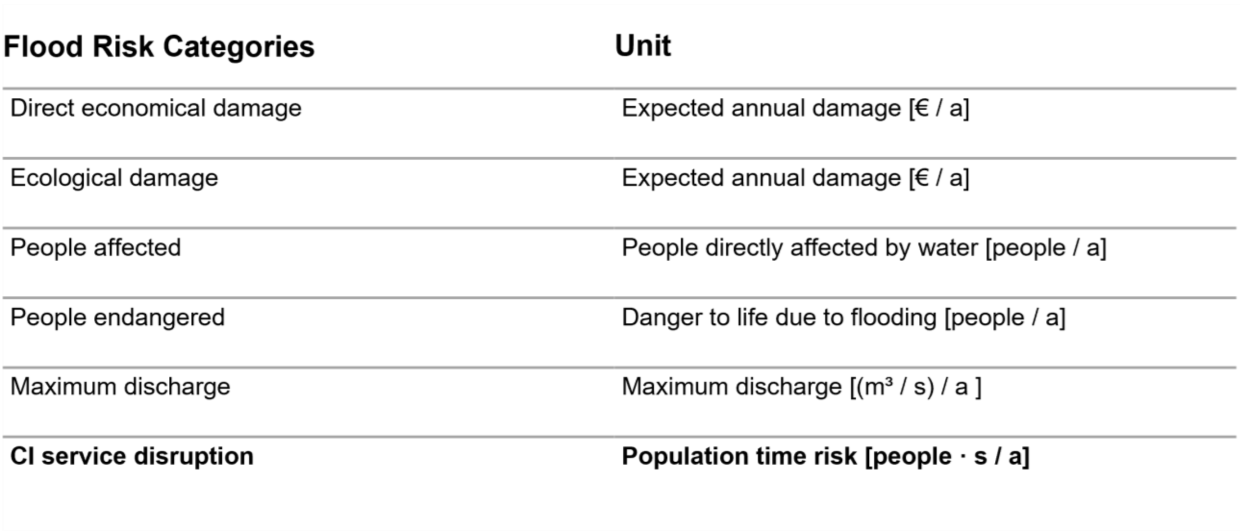
The derivation of risk as a decision-making unit is applied for the consequences to CI as introduced for example by Murdock et al. (2018). The consequences in this calculation are T_{Pop} as the quantified consequences of flooding for CI. The sum of all products of T_{Pop} and p_{hyd} per return period scenario k result in the risk of consequences for CI R_{CI} [people·s/a]:

$$R_{CI} = \sum_{k=0}^{n} T_{Pop,sec,k} \cdot p_{hyd,k} \qquad (2\text{-}2)$$

The expected disruption in population time per year can be derived in total or differentiated per sector. In the case study, an example matrix introduces these options.

This adds another type of flood consequence to the range of potentially relevant flood risks that are considered in decision-making processes, as shown in Table 2-3. The well-established consequence types are economic damage, people affected and endangered and maximum discharge which needs to be ensured. The CI service disruption is to be added to the risk matrix of consequences.

Table 2-3: Current flood risk categories complemented by flood risk for CI.



Flood Risk Categories	**Unit**
Direct economical damage	Expected annual damage [€ / a]
Ecological damage	Expected annual damage [€ / a]
People affected	People directly affected by water [people / a]
People endangered	Danger to life due to flooding [people / a]
Maximum discharge	Maximum discharge [(m³ / s) / a]
CI service disruption	**Population time risk [people · s / a]**

2.3.2 Flood Risk Assessment: Acceptance or Denial

After the flood risk analysis is finished, the next phase of FRM is the flood risk assessment. The assessment answers the question whether a determined flood risk is accepted by society through its decision-makers and political representatives. If there is no acceptance of the flood risk, a set of prevention or mitigation measures must be developed. Those risk reduction measures are designed to create an acceptable flood risk situation (Altarawneh et al., 2016). The set of reduction measures is validated again through a risk analysis and then finally selected by decision-makers changing the current flood risk situation. If the flood risk is accepted, preparedness or response measures such as early warnings, action protocols and awareness-raising with all stakeholders need consideration (cf. Figure 2-1).

This paper integrates the consequence category of CI into the assessment step of FRM. For this, a range of aspects can be considered for the decision-making related to acceptance of a flood risk situation. First, there is the quantification of CI flood risk as R_{CI}

(cf. Equation 2-2). Additionally, the CI modelling approach identifies the areal spread of CI disruptions per CI sector. This supports the acceptance of potential measures since people affected by disrupted CI are included in the assessment of the flood risk situation. Lastly, the inclusion of CI paves the way for measures not yet considered in flood risk management. The availability of these newly included measures can have an impact whether a situation is accepted or not.

The network characteristics derived from the arrangement of the network elements identify especially vulnerable or influential CI structures without looking at the inundation maps. During the assessment phase, CI structures with high C and V can be combined with flood maps. This gives additional criteria for the acceptance or denial of a flood risk situation. The denial and the acceptance of a flood risk situation lead to the development of measures to improve the flood risk situation.

2.3.3 Risk Reduction—Enabling Prevention and Mitigation Measures for Critical Infrastructure

The denial of a flood risk situation results in the commitment to risk reduction. Current mitigation and prevention measures for risk reduction can range, for example, from technical flood protection and adaptation planning to flood water retention. The types of measures listed previously are referred to as established measures. Favourable measures are tested as scenarios by adapting the boundaries in hydrodynamic or hydrological models.

The risk these scenarios is compared to the risk of the initial state (Bachmann, 2012).

The integration of CI into risk reduction efforts allows consideration of a spectrum of measures that is not included in FRM. The range of possible measures in general is wide and is divided into three categories for this paper: (1) prevention and mitigation; (2) preparedness; (3) response and recovery measures. (cf. Table 2-4). The risk reduction in this paper is achieved using prevention and mitigation measures. Examples of these types of measures are given in Table 2-4. A range of these measures can be integrated into the CI network model, such as the elevation of electrical structures to raise the threshold value for a specific CI point element. Another example is the installation of a redundancy for a CI element.

The possibility to include potential measures in the CI network model allows a CI risk to be derived for particular scenarios. This allows scenarios of CI measures to be compared with the current state and also allows scenarios to be compared with one another. Based on these comparisons, decisions can be made regarding the most effective measures for CI. These decisions can be based on the biggest effects of prevention and mitigation measures on R_{CI} in general or per sector.

The integration of CI into FRM is not intended to replace the consideration of flood risk for population and economy. The aim is to present R_{CI} as another criterion in addition to risk criteria that already exist. The summary of these risk criteria for several consequence categories is derived for the current state as well as for scenarios considering flood risk measures. Further on in this paper, this overview is introduced as a decision-making matrix.

An example of the decision-making matrix is presented in the case study (cf. Section 2.4.4).

Table 2-4: Categorisation of flood risk measures based on the stages of disaster risk management cycle. Examples are shown for primary sectors in general and the energy, water and ICT sectors.

Measure Category	**Prevention & Mitigation**	**Preparedness**	**Response & Recovery**
Exemplary Measures for Critical Infrastructures	No construction of CI in flood prone areas	Training of operational readiness of technical maintenance team	Protection of electrical components through premature switch-off
	Elevated positioning of electrical components	Stocking of spare parts for quicker repair	Prioritization of CI structures with short recovery times
	Redundancies in supply for substations	Raising awareness among the affected population - Stocking at household level	Provision of bottled drinking water
	Increased water level threshold through flood protection	Informing the public about limited network availability	Drying of solid fuels
	Increased battery storage for network masts	Education of CI operators with flood maps	Prioritized repair of ICT structures without redundancy

2.3.4 Coping with Residual Risk

After identifying and pursuing options for reducing flood risk, a certain degree of residual risk remains. Dealing with residual risk is a task for civil society, CI operators and public actors (e.g., operators of flood forecast systems). Again, the focus is on the integration of CI into the FRM approach, at the step of handling residual risk.

From the point of view of CI operators and stakeholders, the results of the flood risk analysis including CI provide valuable information for taking response and recovery measures (cf. Table 2-4). That information can be useful for response measures for emergency services (fire services, ambulance services or police) as well as for CI providers in the water, gas and electricity sectors. These CI suppliers become emergency operators during extreme hazard events and have to take response and recovery measures.

The accessibility of spatial CI network datasets in relation to inundation maps, return periods and, subsequently, risk allows individual CI sectors to improve their prioritisation of response measures such as premature switch-offs of electrical components or the provision of bottled drinking water. Additionally, individual CI operators can benefit from the awareness of interdependencies with other CI sectors and can prioritise their recovery measures.

Participation of CI operators in FRM enables quick connection to other sectors for emergency management. It increases their ability to act. Currently, organisational connections between CI operators are often lacking (Fekete & Sandholz, 2021; E. E. Koks et al., 2022).

Another angle to tackle residual risk is the raising of public awareness and preparedness in areas potentially affected by CI disruption. For CI operators, this involves identifying and notify individual homes that may be under threat of CI disruption during flooding events. This encourages individuals to take action to ensure self-sufficiency and decreases dependency. Examples of preparedness measures at household level are: provision of generators and fuel, freshwater storage in bathtubs or tanks, foregoing minor health treatments in hospitals.

2.3.5 Communication in Flood Risk Management and among Critical Infrastructure Operators and Stakeholders

Integrated concepts of FRM highlight the importance of continuous communication during all stages of analysis, assessment and management (Kuhlicke et al., 2022). For big infrastructure projects, successful communication is built upon the possibilities of public participation (Verein Deutscher Ingenieure, 2015). The flood risk analysis benefits from experts and planners communicating information to civil society and vice versa. Public participation during hazard modelling, also known as participatory modelling, ensures a robust outcome (Petersson et al., 2020). During the assessment, it is important to communicate bi-directionally about the decision-making process. Communication is also important for identifying potential measures and the presence of residual risk (Chan et al., 2020; German Federal Ministry of Education and Research, 2020).

The integration of CI into FRM communication is another aspect of this paper. Figure 2-1 highlights that communication is an ongoing effort. Therefore, it is particularly important to involve CI operators and stakeholders continuously. There are five good reasons for the involvement of CI operators and stakeholders: (1) the acquisition of data and information for the flood risk analysis; (2) the development of feasible and realistic prevention and mitigation measures; (3) the generation of awareness among CI operators for flood risk; (4) the development, communication and implementation of preparedness, recovery and response measures; (5) the organisational cross-linking of CI operators with each other.

The five reasons given are all addressed by the CIrcle method previously mentioned (cf. Section 2.2). In this paper, the CIrcle method is used to integrate CI operators into FRM communication and is accompanied by a web tool (K. M. de Bruijn et al., 2019; Deltares, 2021).

The first step of the CIrcle method is to identify local core CI operators and particularly the relevant CI sectors for the area of interest, depicted as circular sectors in Figure 2-3. Contacts are established and information is gathered for the individual sector; this is also in preparation for the second step. In the second step, the operators and stakeholders participate together in a workshop. Based on their expert judgement, the potential dependencies of CI sectors are gathered and summarised in the CIrcle. Participants are asked to state their individual positions and the potentially relevant interdependencies of their sectors during a flood event, as marked by the connecting elements of the circu-

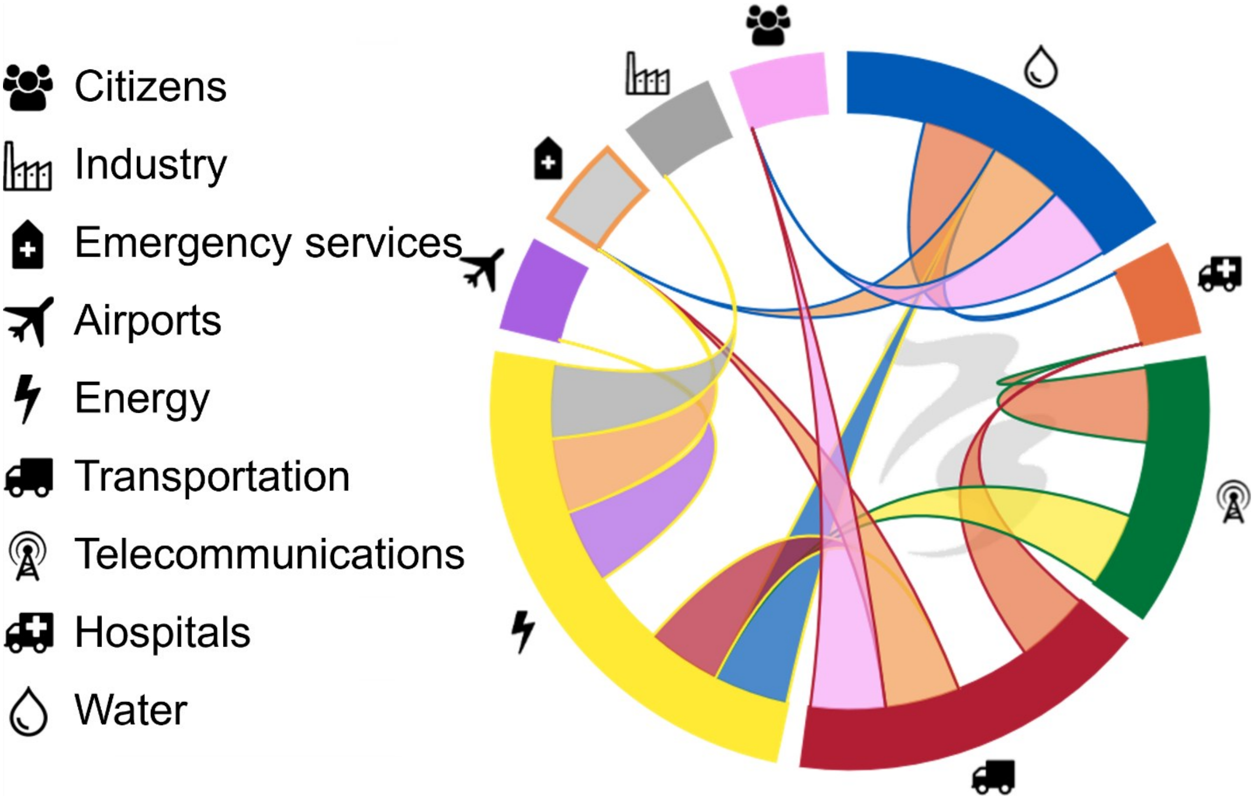


Figure 2-3: Fictional composition of a “CIrcle” depicting the cascading effects within CI sectors (de Bruijn et al., 2019; Deltares, 2021).

lar sectors. The third and concluding step offers an outlook on where the cascading effects are identified, and potential measures to break cascading effects are discussed. The three steps of this method align with the analysis, assessment and measure planning.

Each application of this method delivers results specific to the CI networks in the area of interest and also depends on the background of the participating CI operators and stakeholders. The CIrcle method can accommodate a qualitative discussion focussing on the CIrcle itself (cf. Figure 2-3) and the dependencies. The method can also be used to derive more quantitative information including hazard, consequence and risk-based maps. The more quantitative contributions participants give during this exchange, the more additional information and data flows into the CI network model setup.

To ensure development towards control implementation and an effectiveness evaluation as concluding steps of risk management (Ani et al., 2019), it is of crucial importance to address the question of how to trigger suggested mitigation measures. Cascading effects of the flood impacts and consecutive network disruptions cause a cascade of responsibilities for initial action-taking and resource allocation on the operator side. This carries the risk that no action will be taken at all after such an analysis. To overcome this issue, communication is highlighted extensively in this workflow’s description.

2.4 Case Study in Accra and Critical Infrastructure Integration into Flood Risk Management

The integration of CI into FRM is presented in a case study in Accra, the capital of Ghana. The PARADeS (participatory assessment of flood-related disaster prevention and development of an adapted coping system in Ghana) project provides the framework for this work, including opportunities for contact with the relevant stakeholders (German Federal Ministry of Education and Research, 2020). Key partners are the Ghanaian National Disaster Management Organisation (NADMO) and Water Resources Commission (WRC) (Almoradie et al., 2020).

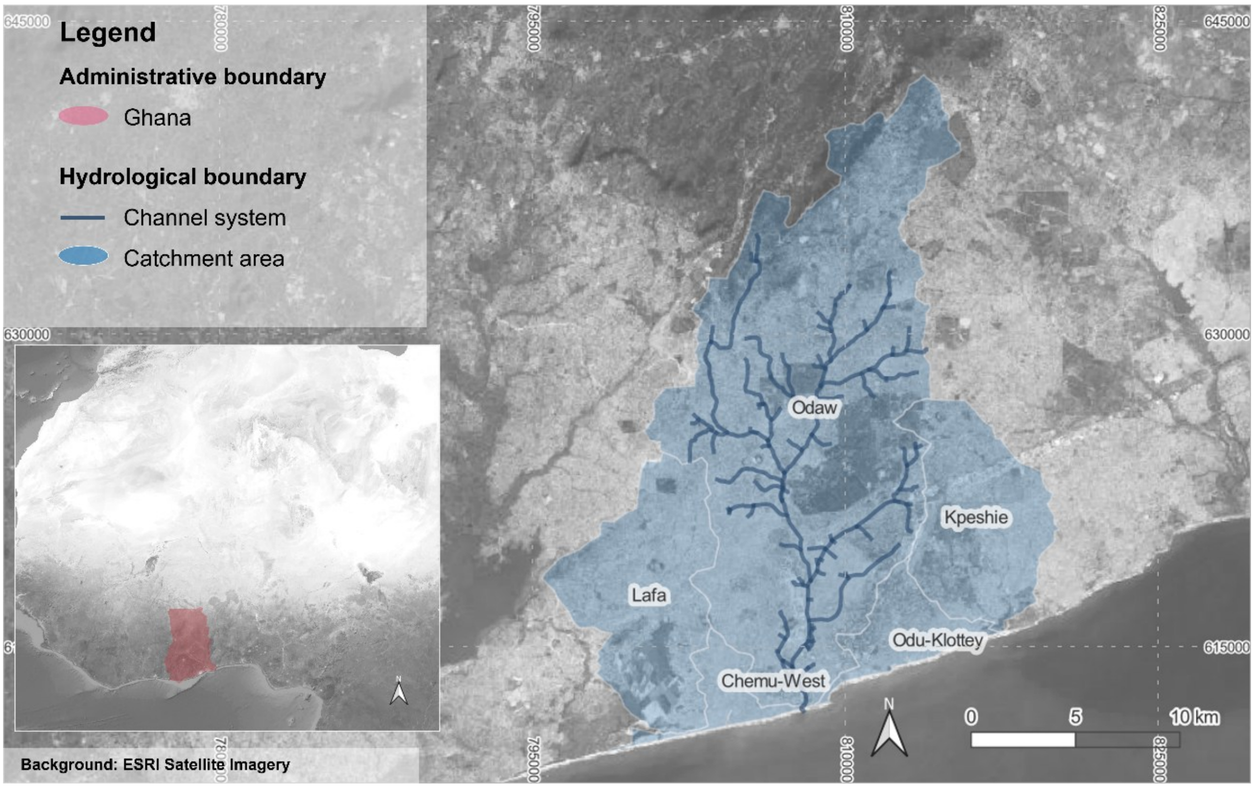


Figure 2-4: Geographical location of case study area. (Left): Western Africa highlighting Ghana in red and defining the boundary around Accra. (Right): the river catchments considered.

The flood risk analysis is catchment-based, focusing on the Odaw River catchment and considering CI in the surrounding catchments of Lafa, Chemu-West, Kpeshie and Odu-Klottey, as shown in Figure 2-4. The Odaw catchment covers about 271 km^2 and is located close to the sea. The total size of all the catchments is roughly 360 km^2, and the area is predominantly urban. For the hydraulic analysis and the analysis of consequence, the ProMaIDes framework is used (Bachmann, 2023). Hydraulic calculations are made with a combined 1D-2D approach. A digital elevation model (DEM) with a 30 m resolution is used, and the floodplains are represented by 414,000 25 m × 25 m raster cells. Synthetic block rain events of 24 h with three different return periods (T10, T100, T1000) are applied, uniformly distributed over the whole area. The typical flood consequences are based on an economic damage model using stage-damage functions as well as land usage data (Huizinga, 2018; Huizinga et al., 2017). To establish the consequences for people, high-resolution population density maps have been combined with the approach to estimate the loss of life due to flooding (Jonkman, 2007; Meta - Data for Good, 2023).

2.4.1 Critical Infrastructure Network Model Setup

The CI network model shown in Figure 2-5 evolved in steps, resulting in three versions of the model. The first version (V1) was generated with no stakeholder interaction and was derived from publicly available data such as OpenStreetMaps and other web mapping services (OpenStreetMap contributors, 2017). The second version (V2) is a modified version including feedback from individual stakeholder interaction based on interviews. The third version (V3) was derived from feedback from a collaborative stakeholder participation meeting involving the CIrcle method. This stakeholder participation meeting was organised in the form of a CIrcle workshop, as described above (cf. Section 2.3.5). Figure 2-6 shows how the different participation levels raised the number of CI network elements, which underlines the benefit of involving CI stakeholders in the FRA. Additionally, the model versions including individual and collaborative stakeholder in-

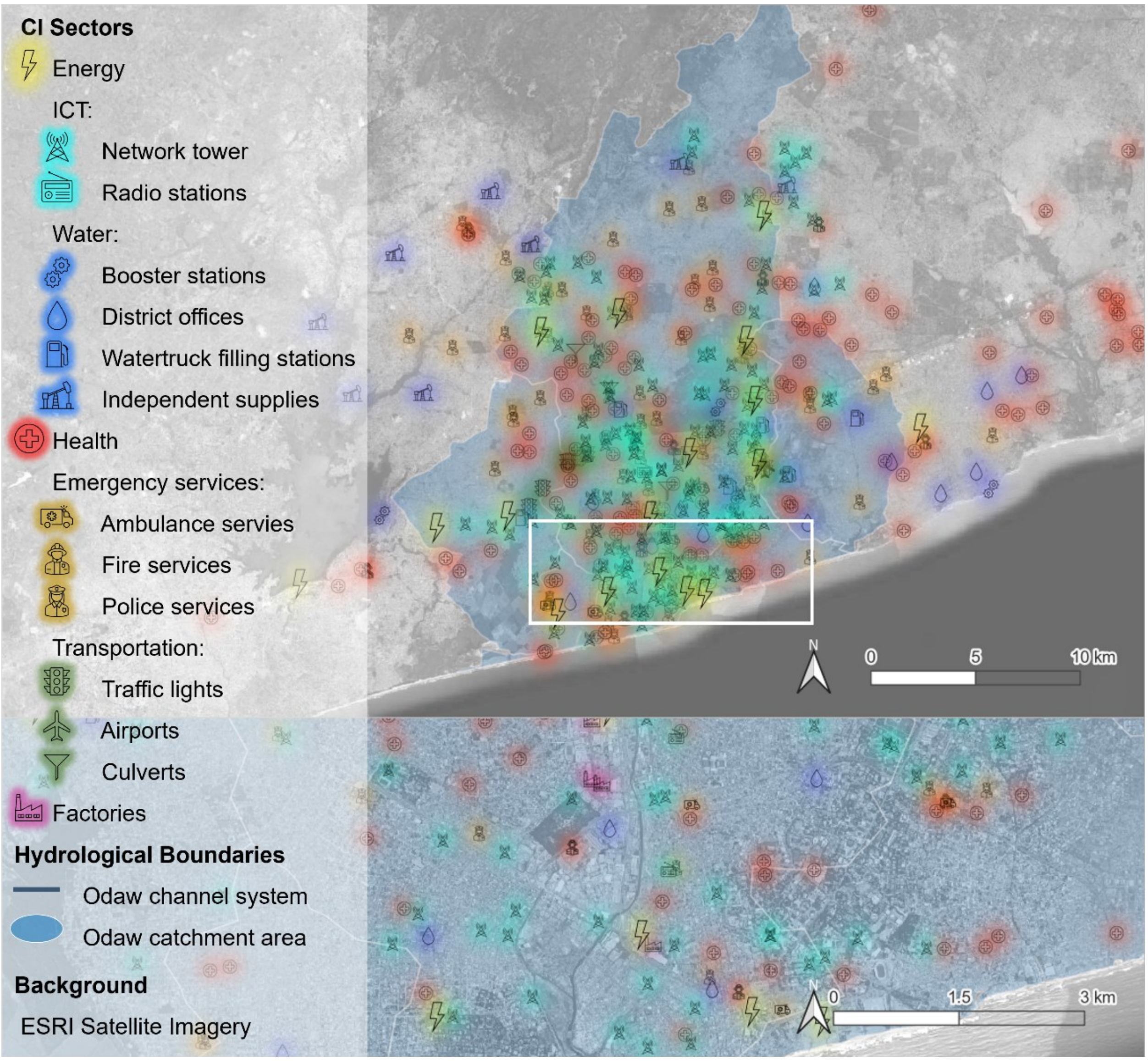


Figure 2-5: Overview of CI network model of Accra, including locations highlighted by CI stakeholders.

volvement do not vary greatly by the number of CI network elements but by the quality and relevance to the CI stakeholders. The point elements added to the third CI network model version are highlighted as particularly relevant to the CI stakeholders during the participatory sessions. An example for this case study are three major radio stations, which were identified during the workshop and are also placed close to the Odaw main channel. They have been highlighted as an important tool of information for the public as well as for the emergency services. Additionally, the most relevant factories in the centre of the area of investigation have been added. For the analysis of the CI network, they play a minor role, but they were included at the request of the CIrcle workshop participants.

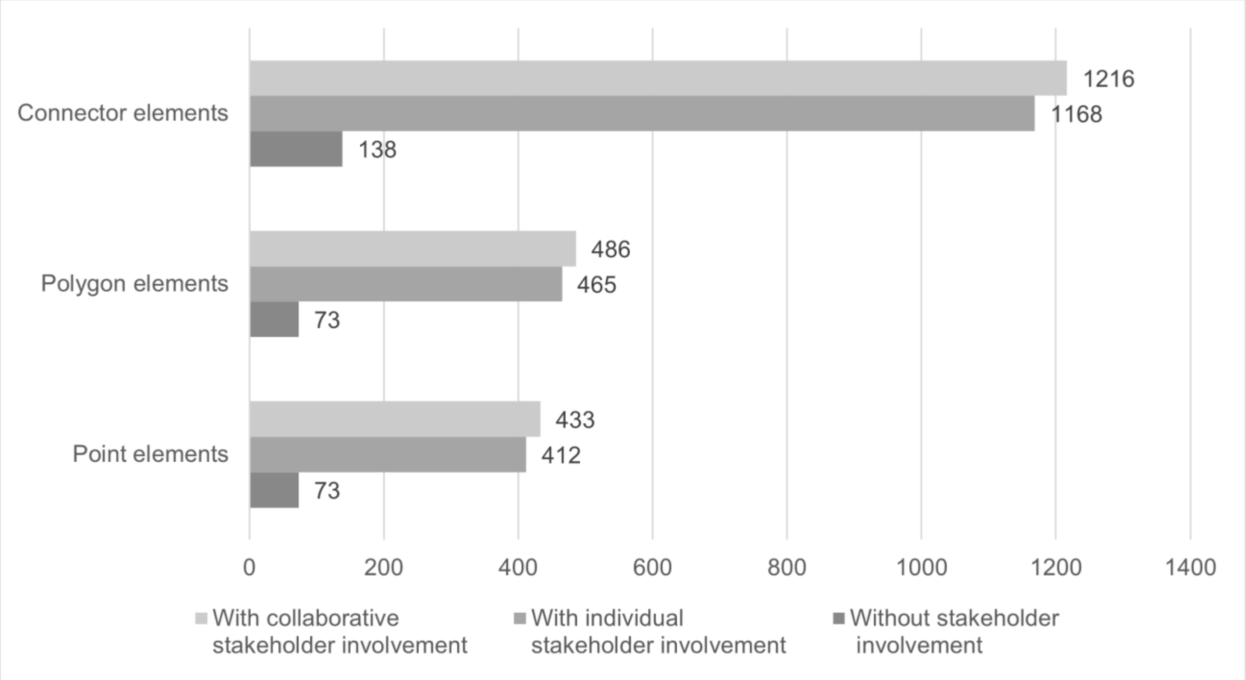


Figure 2-6: Number of critical infrastructure network model elements for the case study in Accra, Ghana at different stages of the model depending on stakeholder engagement levels.

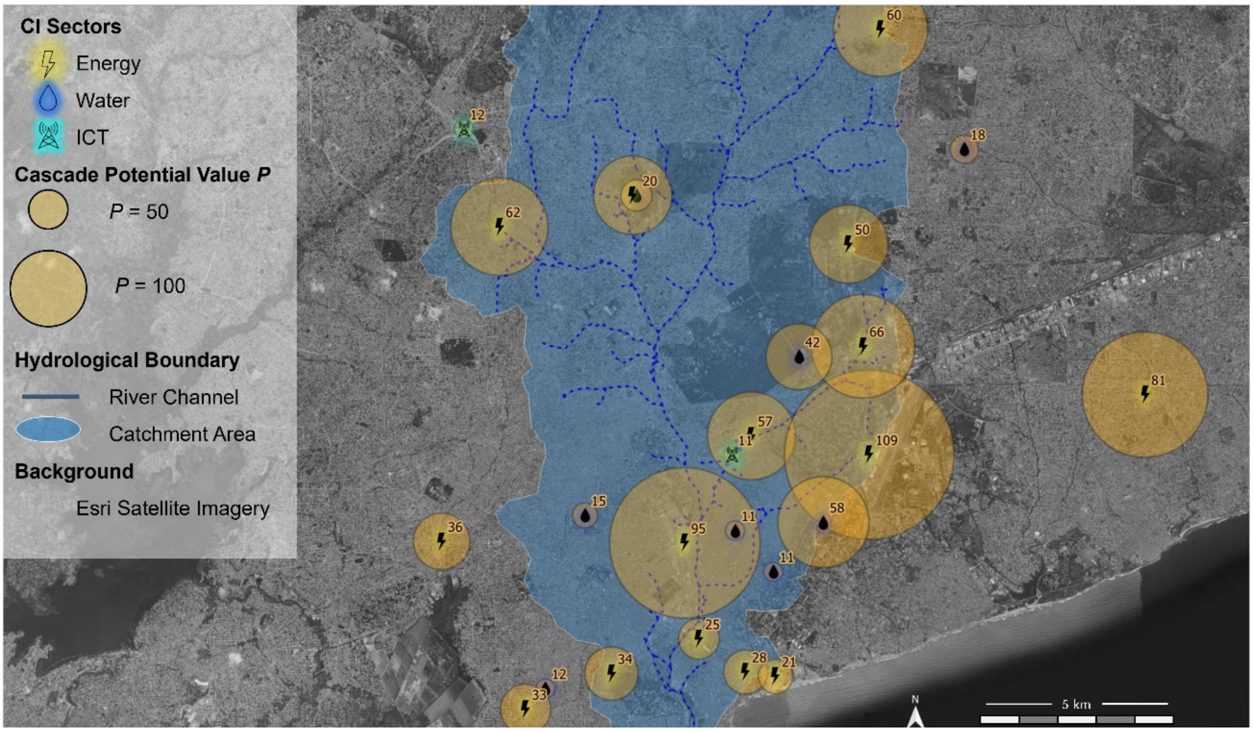


Figure 2-7: Point elements in the CI network model (V2) of Accra with cascade potential values $C > 10$ featuring the energy, ICT and water sectors; 1 km radius equals a cascade potential value $C = 50$ (Schotten & Bachmann, 2023).

2.4.2 Model Characteristics

After the assembly of the CI model, network characteristics are used to describe its characteristics. Figure 2-7 gives an overview of all point elements on the x-axis. The background colours relate to the corresponding CI sectors which are included in this CI network model: electricity, emergency responders, health, fresh water, transportation hubs and telecommunications. The y-axis represents the cascade potential value P, which quantifies the number of end user elements in the CI network disrupted by a failure of this specific point element. The point elements are ranked from the highest C to the lowest. The electricity and the water sectors have the highest C values since they are connected to many more final CI elements that are at the receiving end of a cascade, such as health, the emergency services and the transportation sector, whose points have the lowest C within this model's arrangement. The telecommunications sector is to be found in areas with both high and low C values. The C values characterise the CI network and can help to identify potential sectors and structures for mitigation measures.

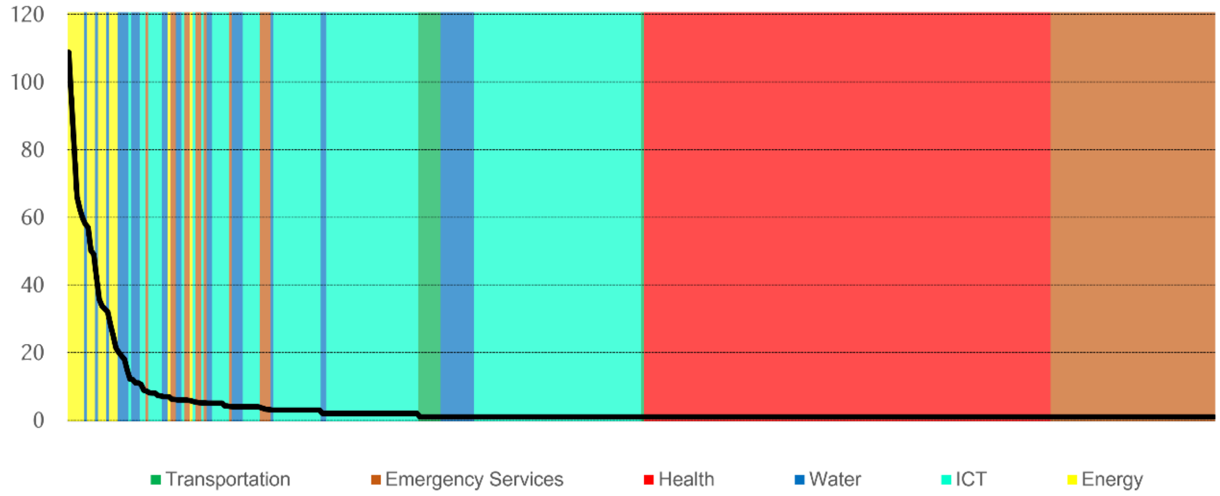


Figure 2-8: Cascade potential value *C* of all CI point elements in CI network model of Accra (V2).

Figure 2-8 presents a graphical overview of the points in the network with the highest cascade potential value *C*. Based on these flood independent network characteristics, potential mitigation measures are developed and discussed with the CI stakeholders.

2.4.3 Results and Risk Matrix

For the results of this case study, the consequences for the economy and population are combined with the probability of occurrence as the flood risk. The economic damages are expressed as the flood risk in USD per year. The risk for people is expressed as the number of people affected and endangered per year. The results of the risk calculation for the typical consequences are shown in the lighter grey section at the top of Table 2-5, the CI network analysis are highlighted in the white part of the table.

The CI consequences derived from the CI network model are then summarised as R_{CI} (cf. Equation 2-2). The range of consequences summarised in this case study cannot be expressed in one unit. Thus, a multi-criteria analysis matrix is created (cf. Table 2-5), referred to as the risk matrix later in this paper. The risk matrix summarises the quantitative results for the R_{CI} per CI sector in every row and the hydrodynamic simulation per return period in every column. The concluding column on the right sums up the risk per sector. The bottom right number concludes the total risk for CI R_{CI} for the current situation of the area of interest.

Table 2-5: Risk matrix including economic damages, population affected and critical infrastructure disruptions for flooding events with different return periods and the accumulated risk.

	Annuality [a]	**HQ10**	**HQ100**	**HQ1000**	**Risk *R* [... / a]**
	Probability of reoccurence p_{hyd} [-]	0.145	0.0495	0.0055	
Classic flood consequences C	**Economic damage [USD]**	295.71 Mio.	465.83 Mio.	631.01 Mio.	**69.41 Mio.**
	Affected [people]	1.12 Mio.	1.3 Mio.	1.49 Mio.	**234,618**
	Vulnerable [people]	12,688	20,099	34,510	**3,024**
Population Time T_{Pop} per CI Sector	**Energy [people · days]**	2.23 Mio.	8.1 Mio.	9.53 Mio.	**776,546**
	Water [people · days]	1.61 Mio.	1.61 Mio.	2.43 Mio.	**326,465**
	Emergency services [people · days]	1.53 Mio.	13.16 Mio.	16.53 Mio.	**964,744**
	Information and communication technology [people · days]	2.03 Mio.	6.15 Mio.	7.47 Mio.	**640,264**
	Health Care [people · days]	3.15 Mio.	7.79 Mio.	11. Mio.	**903,260**
	CI risk sum [people · days]	10.56 Mio.	36.8 Mio.	46.95 Mio.	**3,611,279**

Other results from the CI network model feature the spatial overview of disrupted CI services for every sector derived from the maximum water depth, also introduced as steady state results. The spatial overview of disrupted CI services is generated also for the unsteady state of the hazard model determining the water depth for every time step of the simulation. Figure 2-9 summarises the progression of the unsteady state results for the energy and ICT sector. The progression shows the order in which CI point elements and associated polygon elements disrupt. Additionally, it also shows the order in which CI elements gain their functionality again. The ICT elements disrupted by their intersectoral connection to the energy point elements are disrupted the longest due to the longer recovery time of point elements from the energy sector. This information and data can support the measures for the preparedness and response phase (cf. Section 2.4.4).

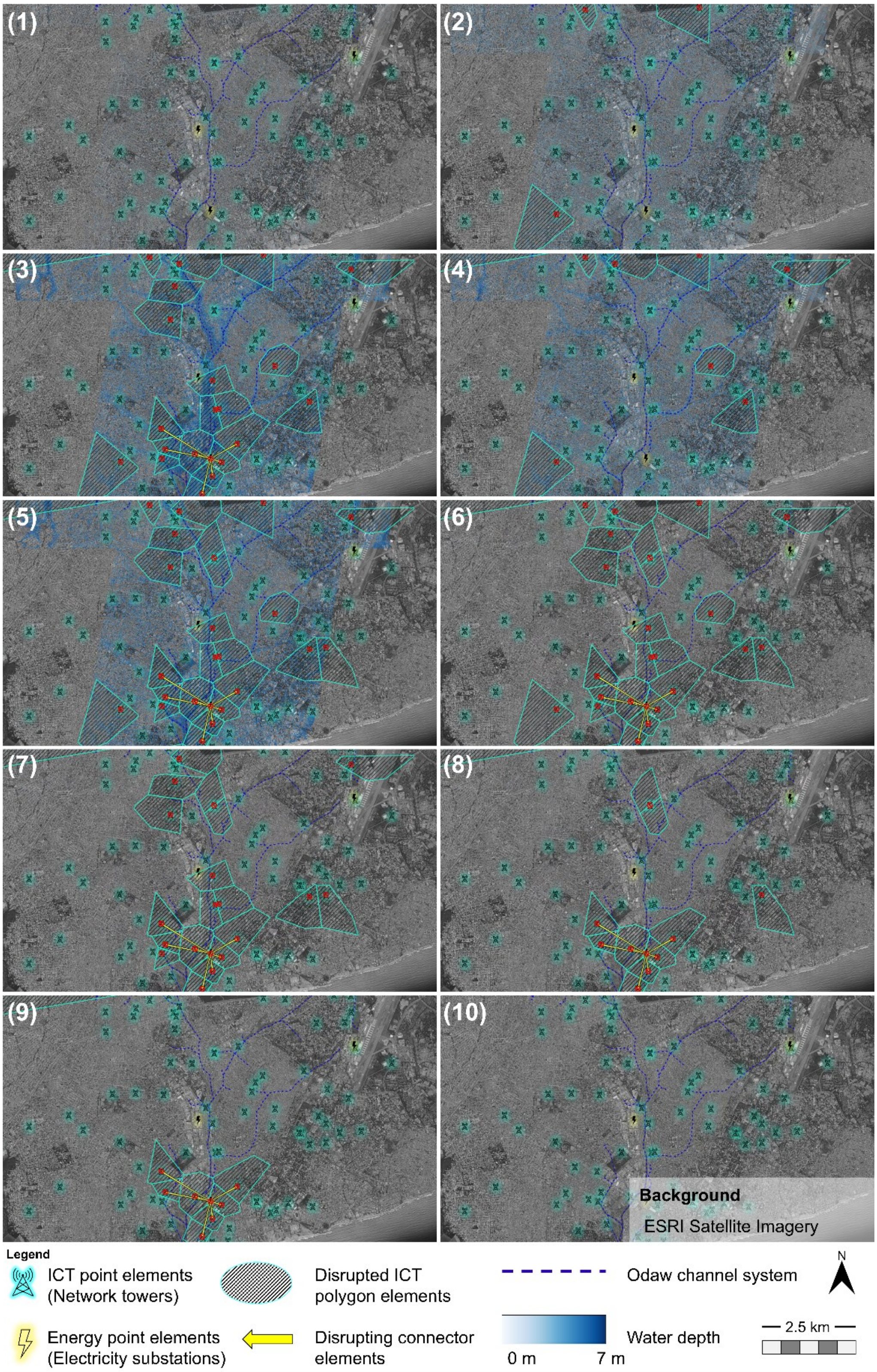


Figure 2-9: Time steps of CI disruptions in a part of the Odaw catchment. Figure partitions 1–10 summarise the order in which the CI point and polygon elements from the ICT sector are disrupted. Energy point elements disrupted transmit the disruption to other ICT point elements. Blue cells in the background indicate a water depth, derived from the hydraulic model for every time step.

2.4.4 Potential Measures for Critical Infrastructures and Decision Making-Matrix

For this case study, two simple measures are suggested and implemented in a copy of the current state CI network model. The analysis of the CI characteristics shows that one electricity substation should be investigated further (cf. Figure 2-10, left). This electricity substation is the source element for 42 other point elements and has a cascade potential value *C* of 105.6. This indicates that the cascading effect would be able to account for a total of over 100 CI elements disrupted by a failure of this substation. Additionally, the information generated for the flood risk analysis confirms that this substation would be affected by a flood event. Thus, this element was selected as an object for a potential mitigation measure that raises the threshold value from 0.2 m to 1 m in the model. In practice, the threshold can be raised by building a flood protection wall around the substation or elevating the technical equipment. This measure is tested in a scenario model and is referred to as Scenario 1 (S1).

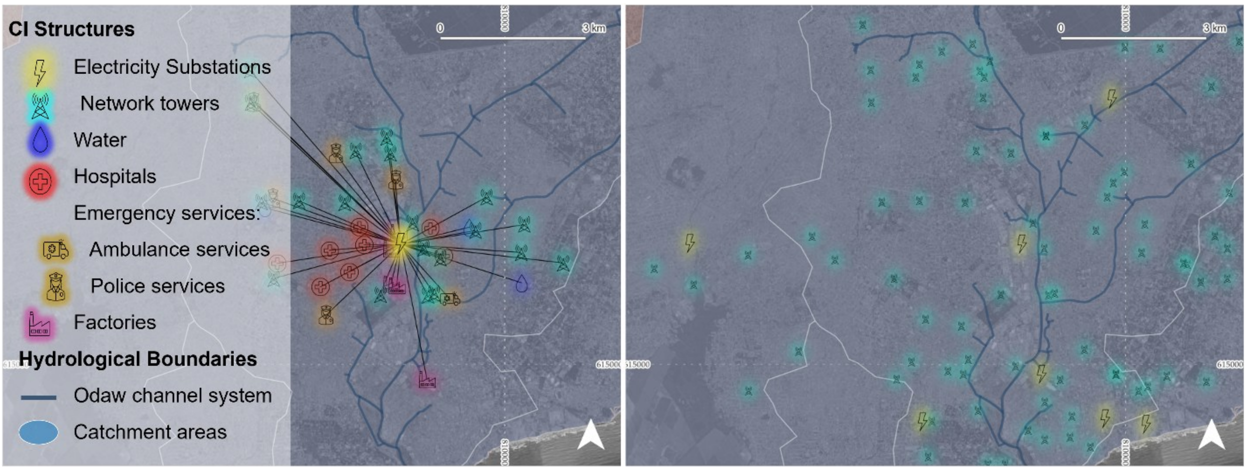


Figure 2-10: Critical infrastructure network elements involved in flood mitigation measures in and around the Odaw river system. (Left) In the centre, an electricity substation is highlighted which is connected to 43 sink elements. (Right) Mobile network towers and electricity substations.

The second scenario-tested measure aims to reduce the impact on the mobile network system by decreasing the recovery time of affected mobile network towers. In reality, a modular approach for the internal energy storage components and the stockpiling of spare parts are suggested in order to reduce the recovery time. This scenario is referred to as Scenario 2 (S2). Figure 2-10, right, depicts the mobile network towers as well as the electricity substations that supply the energy.

The comparison of the risk sum of every sector and particularly the difference compared to the current state offers robust guidance for decision-makers in order to quantify the effectiveness of both scenarios. Table 2-6 compares the two measures of S1 and S2 in a decision-making matrix derived from the model analysis, with the current state based on their risk. It highlights the difference of the flood risk regarding the disruption of CI services per sector. Compared to S2, S1 shows a bigger spread of influence on the R_{CI} of other sectors but a smaller difference in total. Scenario S2, which shortens the recovery period of mobile network towers, affects fewer sectors but has a much bigger magnitude in the difference of R_{CI} compared to the current state. Once the price for these measures is derived, the price and R_{CI} reduction can be compared in order to validate the best option.

Table 2-6: Decision-making matrix comparing current flood risk with two mitigation measure scenarios S1 and S2 using the CI disruption in population time per year.

	Flood risk	... in the current state (CS)	... with protected substations (S1)	Differences (S1-CS)	... with batteries in network towers (S2)	Differences (S2-CS)
Classic flood consequences C	**Economic damages [USD]**	**69.41 Mio.**	69.41 Mio.	0	69.41 Mio.	0
	Affected [people]	**234,618**	234,618	0	234,618	0
	Vulnerable [people]	**3,024**	3,024	0	3,024	0
Population Time T_{Pop} per CI Sector	**Electricity [people · days]**	**776,546**	322,896	-453,649	776,546	0
	Water Supply [people · days]	**326,465**	26,470	-299,995	326,465	0
	Rescue Services [people · days]	**964,744**	639,490	-325,255	964,744	0
	Passenger Transport [people · days]	**0**	0	0	0	0
	Information Technology [people · days]	**640,264**	226,246	-414,018	640,264	0
	Health Care [people · days]·	**3,611,279**	341,437	-3,269,842	903,260	-2,708,019

2.5 Discussion

The integration of CI into the steps of FRM functions. As regards theoretical integration and practical application, a few challenges and limitations arise. The lack of connection between flood risk management and CI operation is the primary challenge. Little awareness and collaboration between CI and FRM is present on a day-to-day basis, leading to decreased quality at every step of FRM. Ongoing participation processes are designed specifically for the context of multisectoral CI operations and proven to benefit the CI network model generation (cf. Section 2.4.1). These participation processes have enormous potential to bridge data and information gaps. An important condition for these participation processes is the commitment of CI operators to spend resources on this participation and the willingness of flood risk managers to invite CI stakeholders. The resources of CI operators refer here to specific staff who are in charge of operation and maintenance, and also the accessibility to network and operations data.

The flood risk analysis for this CI network relies on a range of data inputs that determine the quality of the model results. On the one hand, CI data is sensitive due to the potential for damage if the data comes into the possession of people and parties with a harmful intent. Data protection regulations also make accessibility and application difficult. On the other hand, the CI asset data relevant for the modelling process has specific requirements, is scarce and often not gathered with the intent to represent multisectoral cascading effects or natural hazard events (e.g., data on interdependencies of CI structures, spatially homogeneous information on CI users per asset, time of disruption due to flooding, hierarchical structure within CI sectors, location of interdependent CI assets and crosssectoral and sectoral redundancies). Therefore, public institutions and CI operators need to be more willing to assemble and share datasets. This could ensure the quality of CI network model outputs and allow CI network modellers to conduct validation. The literature and field reports on past events from other investigation areas supplement and substitute missing data (E. E. Koks et al., 2022).

The lack of precise data sets leads to a range of assumptions and the generalisation of specific expert judgements. These assumptions can be categorised as extrinsic and intrinsic assumptions. Extrinsic model assumptions are made during the specification of network element properties and the arrangement of these elements. Extrinsic model assumptions replace datasets and have a potential impact on the quality and significance of the model output. One example for an extrinsic model assumption is the impact of preparedness measures on recovery times. The reduction of the recovery time is ensured by the stocking of spare parts, but this is hard to quantify without close contact with CI operators and is thus assumed for the network element properties.

Intrinsic model assumptions describe the methodology of the modelling approach and its inherent limitations. The binary state of the CI point and polygon elements is one example of inherent limitations. It is either fully functional or disrupted, as explained in Schotten and Bachmann (Schotten & Bachmann, 2022b). This intrinsic assumption and also the extrinsic model assumptions mentioned above add a level of uncertainty to the model. This uncertainty needs to be communicated with CI operators and other parties involved as data and information sources. It is recommended that the data needs for CI modelling are categorised and defined further.

In an ideal world where all desired information and data is available, the integration of CI into FRM, as presented in this paper, would help to create a society that is more robust and resilient in the event of a flood.

2.6 Conclusion

This paper presents a step-by-step integration of CI networks into FRM. The integration of CI begins at flood risk analysis stage with a CI network modelling approach that allows consideration of the consequences for critical infrastructure. This includes sectoral and intersectoral cascading effects, a quantification of CI service disruptions as population time T_{Pop} (cf. Equation 2-1) and also information on the areal spread of CI network disruptions. Based on the consequences, the CI flood risk is introduced as R_{CI} (cf. Equation 2-2). R_{CI} is arranged in a flood risk matrix to support decision-makers during flood risk assessments. Further support for decision-making at the assessment stage is delivered with the network characteristics C and V, which allow information about especially vulnerable and influential CI elements in flood prone areas to be included. A catalogue of measures for CI is introduced based on the stages of the disaster risk management cycle. The integration of CI into FRM shows that these measures can now be considered in measurement planning. The capacity to act regarding flood risk reduction and also regarding coping with residual flood risk has been increased. The aspect of ongoing communication between flood risk stakeholders is also addressed in this paper, by including CI operators more closely in all steps of flood risk management.

With the test case, it is proven that the suggested integration of CI into FRM is possible. A CI network model has been used to derive T_{Pop} and R_{CI} for CI from six different sectors. The CI network model results showed the potential to support the flood risk assessment. The CI network characteristics were proven to benefit the identification of potential mitigation measures. The measures have then been implemented successfully in CI network model scenarios and, in a decision-making matrix, were compared to the initial state of the area of investigation. In the case study, the ongoing participation of CI operators was demonstrated to be beneficial for individual FRM steps. In conclusion, it can be said that the integration of CI into flood risk management has been proven effective and is now ready for practical implementation in situations where there is collaboration between CI operators and flood risk management.

3 CRITICAL INFRASTRUCTURE NETWORK MODELLING FOR FLOOD RISK ANALYSES: APPROACH AND PROOF OF CONCEPT IN ACCRA, GHANA

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Journal of Flood Risk Management 2022, 16(3)

DOI: 10.1111/jfr3.12913

In flood risk analysis, it is state-of-the-art to determine the direct consequences of flooding for assets and people. Flooding also disrupts critical infrastructure (CI) networks, which are vital in modern society. Cascading effects in a CI network can exceed the hydrological catchment boundaries. The effects of directly impacted CI cascade to other infrastructures, which are thus indirectly affected by a flood. A robust modelling approach of critical infrastructure networks is a basis for including these effects in flood risk analysis. One challenge is to balance the simplicity of the modelling approach, the reproduction of a CI network's complexity and the decisions made based on potential model outputs. In this paper, a topology-based modelling approach of CI networks for catchment-wide flood risk analyses is proposed. The basic model elements are points, connectors and polygons, which are utilised to represent a multisectoral and layered CI network. The newly defined approach is implemented as CI network module to the state-of-the-art flood risk analysis framework PROMAIDES. *It analyses the CI's direct and cascading impacts as well as the indirect disruption of CI services triggered by flooding scenarios. It quantifies the consequences by determining the number of disrupted CI users or the disruption time. A proof of concept in Accra, Ghana demonstrates the method's capabilities.*

3.1 Introduction

An extreme natural event becomes a catastrophe or hazard through contact with society. Ever-expanding cities and their growing critical infrastructure (CI) supply networks affect the potential risk through extreme events by increased exposure as well as insufficient preparation and adaptation (Ferguson, 2021). The impacts on society, for example emitted by flooding, are transmitted through expanding and more closely webbed CI networks. More understanding and appreciation are needed of network analytics in order to improve flood risk analyses and subsequently flood management. Flood consequences, as one element of flood risk analyses, can be differentiated according to their tangibility as well as their cause of disruption (Patt & Jüpner, 2020). Table 3-1: Flood consequence categorisation based on monetary impact and cause of impact. shows one possible way of categorizing flood consequences based on Merz (2006). Direct flood consequences are caused by flood waters, whereas indirect consequences are not caused by contact with water or are outside the area and time period of a flood. Tangible consequences can be measured in monetary terms. Intangible consequences are not effectively represented as a monetary value (e.g., loss of life). The field of direct, tangible flood consequences has been researched in detail for several years (Delalay et al., 2020; Huizinga et al., 2017; Wagenaar et al., 2018). The analysis of direct, intangible flood consequences is migrating from state-of-the-science to state-of-the-art approaches as an integral part of a flood risk analysis (Bachmann & Schüttrumpf, 2014; Jonkman, 2007; Jüpner et al., 2018; Kreibich et al., 2017; Merz et al., 2018; Wagenaar et al., 2019). The analysis of indirect and intangible consequences of flooding is receiving very little acknowledgement in current practise (Dassanayake, 2022). The presented categorisation is widely used in FRM practises but does rarely include CI.

CI provide services and goods that are essential and vital for societal functions, health, safety, security and the economic and social well-being of people (Burzel et al., 2014; Federal Office of Civil Protection and Disaster Assistance – BBK, 2022). CI are the technical structures relevant for supplying those services and are organised in sectors such as energy, water, nutrition, information and communication technology (ICT), health, transportation and more (Federal Office of Civil Protection and Disaster Assistance – BBK, 2022). CI networks are formed by considering the interdependencies of these individual CI sectors (CIPedia contributors, 2023). Fekete (2019) extensively defines the cascading effect as transmission through the CI network of a direct CI disruption caused by natural or manmade hazards. Indirect consequences occur in the form of CI service disruptions and are amplified by cascading effects. Table 3-1 is complemented by two types of flood consequences considering the role of CI. During Hurricane Sandy, for example, direct and also indirect disruption of the energy, water and transport sectors could be observed (The New York Times, 2012). The 2021 flood events in Western Europe affected energy and water supplies as well as ICT and other CI sectors for days, weeks and months (Fekete & Sandholz, 2021; WDR, 2021). In both cases, cascading effects led to consequences beyond the directly impacted area. Kuhlicke et al. (2021) stated in the aftermath of these events that approaches for quantifying the cascading effects of CI networks during hazard events are required. The structured integration of CI services and cascading effects into flood risk analyses is still rare. Vorogushyn et al. (2018) call for the integration of indirect flood consequences beyond the flooded area due to the failure of CIs into the flood risk analysis. De Bruijn et al. (2019) and Pant et al. (2018) point out that more consideration should be given to CI in the research of flood resilience.

Ouyang (2014) provides a set of categories for CI network modelling techniques which contains among others: empirical methods, agent-based and system dynamics-based methods, network-based methods and high-level architecture. For this article, a small range of the modelling approaches is introduced. Based on this, the relevant factors for the presented CI network modelling approach are chosen.

Table 3-1: Flood consequence categorisation based on monetary impact and cause of impact.

	Tangible (Monetary)	**Intangible** (Non-Monetary)
Direct (contact with water)	Buildings, Households, Vehicles	Affected People
	Industry, Business	Ecological Values
	Agriculture, Forestry	Cultural & Personal Values
	Infrastructure	**Critical Infrastructure (CI) Disruption**
Indirect (no contact with water)	Business & Logistic Disruption	Loss of Trust in Region
	Cost of Emergency Measures	Psycho-Social Consequences
	Unavailability of Agricultural Land	Epidemics and State of Emergency
		CI Service Disruption & Cascading Effects

Ani et al. (2019) defined empirical methods as established techniques to account for effects on CI. This method type derives network information from expert knowledge and gathers recurring patterns of CI cascades (Murdock et al., 2018). The empirical methods can be combined with quantitative tools depending on the amount and type of information gathered (Murdock et al., 2018).

Agent-based and system dynamics-based methods are designed to react to external or internal impulses according to Brown (2007) and Rinaldi et al. (2001). For agent-based methods, the smallest decision-making units or individuals are considered and form a bottom-up hierarchy of the model dynamic. By contrast, system dynamics-based approaches depict the adaptivity of networks as a whole and change the metrics of the entire system to form a top-down method (Ouyang, 2014).

Network-based methods utilise network elements such as points and connectors, also referred to as nodes and edges. These elements are associated with states of operation, for example, functional or disrupted, which determine the network elements' operability. The boundary of CI analyses ranges from local to regional or even international, as shown by Verschuur et al. (2022). The network-based methods can be further classified in flow-based modelling and topology-based modelling approaches. Flow-based methods focus on goods and services delivered by CIs, whereas topology-based methods focus primarily on the topological presence of a CI, as Mühlhofer et al. (2023) apply in a general natural hazard modelling approach for cascading effects. Flood risk analyses using these methods consider, for example, the effect of flooding on roads and the potential damage due to loss of transport connectivity (Scoccimarro et al., 2020) as well as the resulting economic damage (van Ginkel et al., 2020). Emanuelsson et al. (2014) describe a model focussing on the water sector and its incoming dependencies from the energy sector. It combines a probabilistic flood assessment with an analysis of potential cascading effects on other compounds in the water sector. For a more detailed explanation of the available modelling approaches, refer to Ouyang (2014).

The methods outlined above can be combined if necessary. Pant et al. (2018) use a combination of the flow-based method and the topology-based method to model flood inundation impacts on a CI network. The energy sector's electricity grid is modelled in a hierarchical order depending on the relevance and functionality in the supply grid. The direct impact on the electricity infrastructure and the indirect impact caused by electricity outages are one output of the model and account for the cascading effect. "Electricity grid customers disrupted" is used as a key metric for the disruptiveness of a cascade and provides an approach to quantifying the CI's cascades (Murdock et al., 2018; Pant et al., 2018).

Another method is defined by Ouyang (2014) as a high-level architecture method which is characterized by the ability to combine multiple complex sectors in one model. Arosio et al. (2020) and Pant et al. (2017) provide examples of this modelling approach.

The objective of this article is to define a new CI network modelling approach, focusing on theory, practise and proof of concept. In the introduction to this article, available approaches were briefly outlined. Based on these, the new CI network modelling approach and its basic elements are defined. Additionally, element properties, network characteristics and the calculation procedure are explained. A proof of concept based on a case study outlines the applicability and potential benefits of the presented approach. The CI network modelling approach is used to quantify CI consequences and to highlight affected areas and cascading effects for flooding events in Accra (Ghana). Finally, the results and limitations of the approach and the added value of integrating CI disruptions in flood risk analyses are discussed and concluded.

3.2 Critical Infrastructure Network Modelling Approach

One purpose of this modelling approach is to supply another metric and a robust modelling approach for decision-making in flood risk management by adding another consequence type to flood risk analysis. Another purpose is to highlight vulnerable points' dependencies in the CI network for which mitigation measures are relevant and show the spatial extent CI disruptions can potentially have. The intention is not to represent the CI network and its service precisely, but to provide a rough overview for a specific topic to the overarching perspective of flood risk managers.

The functions represented by this modelling approach focus on the basic service that CI supplies to civil society, based on the exposure of individual CI elements. A combination of the number of users disrupted and the duration of disruption is chosen as a metric for this modelling approach, as suggested in the empirical approach by Murdock et al. (2018).

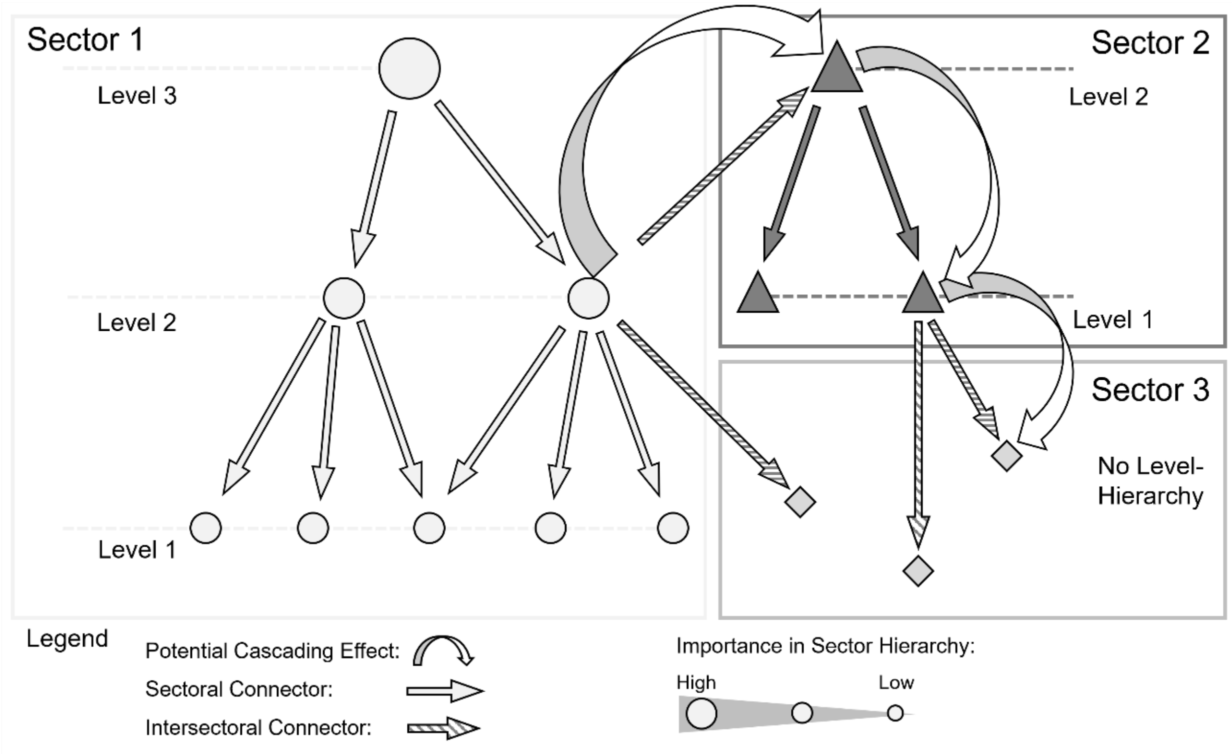


Figure 3-1: A schematic network high-level architecture modelling approach including three CI elements from three sectors. The point elements are arranged on sector levels and form a hierarchy for sector 1 (points) and sector 2 (triangles). Sector 3 (diamonds) is not organised hierarchically.

The structure of the new modelling approach presented here combines the network topology-based approach comparable to Pant et al. (2018) and the high-level architecture modelling approach for flood risk analysis. Figure 3-1 shows how a model schema based on the combined methods is shaped. The hierarchical representation of one sector is extended by including schemas for two additional sectors whose CI elements are represented as triangles and diamonds. In addition to connections within the sector marked by unicoloured arrows and defined as sectoral connectors, this schema also contains striped arrows, highlighting intersectoral dependencies. This enables the method to consider cascading effects within (sectoral) and across (intersectoral) CI sectors and merges them into a system considering interdependency.

3.2.1 Definitions and Model Elements

In this article, the defined modelling approach is referred to as the CI network module. At the beginning of the explanation of the CI network module, definitions of the model elements and their attributes are outlined. The CI network module describes network models utilising three types of CI elements: point, polygon and connector elements. Table 3-2 summarises the properties necessary to define the three element types. Every point element is assigned to a CI sector and level, in addition to the obvious properties (index, x and y coordinates, name). The level indicates the relevance within one sector. The higher a point element's level, the more important it is for the sector's functionality. Additionally, it is a requirement to have data on the threshold for every point element, which defines the water depth causing a disruption. Exceedance of the threshold value at a point element results in a disruption and is cascaded through the connector elements to other point and polygon elements. Once disrupted, the recovery time indicates the time of disruption for an inundated point element. The point elements and the polygon elements are binary, which means they are either functional or disrupted.

Connector elements define other CI elements' directional dependencies. Connector elements indicate that a sink point element relies on the functionality of a source point element. Additionally, connector elements are classified as either sectoral or intersectoral connectors.

Polygon elements define the spatial extent that their source point elements are associated with, or at least partially associated with. In addition to the basic attributes (polygon index, sector index, name and coordinates) the polygon is defined by the number of end-users or consumers it supplies with a service. Polygons are always end-user elements and thus associated with a number of end-users, but if no spatial representation is necessary point elements can be end-user elements, too. Polygon elements and end-user point elements are always only sink points and do not have outgoing connectors.

Within the CI network module, four CI sectors are defined as primary CI sectors and services (Rinaldi, 2004). These are: the energy sector, the ICT sector, the water sector and the waste management sector. The primary CI sectors are chosen as such due to their physical attributes and their standardised operating principles, comparable to (Rinaldi et al., 2001). Primary sector structures are connected to structures from the secondary sectors. Secondary sectors are not internally driven by physical interdepend-

Table 3-2: Attributes of input elements of the CI network module: points, polygons, and connectors.

Element	Input Attributes	Description
Point (Nodes, Vertices) ○	Point-, Sector Index	Unique identification for point; Sector specific identification.
	Sector Level	Quantitative representation in the hierarchy per sector.
	Threshold	Waterlevel threshold for which exceedance results in failure of CI structure
	Recovery Time	Time until functionality of a structure is regained
Polygon (Area) ⬠	Polygon-, Sector Index	Unique identification for polygon; Sector specific identification
	End Users	Number of users represented by polygon
Connector (Edge) ⇨	Connector Index	Unique identification for connector
	Source- , Sink Index	Source point identification or sink point/polygon identification
	Type of Source and Sink	Sector identification of source and sink element

encies but by logistic, cyber and geographical interdependencies. Secondary sectors include, for example, the emergency and health sector, the state and public sector and the transport and logistics sector.

3.2.2 Critical Infrastructure Network Characteristics

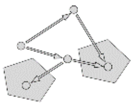
After the setup of the model, the network characteristics and attributes of individual CI elements are derived. They show that networks are more than the sum of their individual components (Ferguson, 2021). The network characteristics allow highlighting of the role of individual CI elements with outstanding importance for network reliability, without taking the hazards into account.

Table 3-3 lists the network characteristics derived from the CI network's point and polygon elements. Two characteristics are commonly used in network models, as shown by Arosio et al. (2020), to characterize point elements: the hub value H, summarising the number of outgoing connectors per point element, and the authority value A, describing the incoming connectors per point element. Point elements with a high H indicate a high potential to affect other elements of the CI network in the event of a disruption; complementary to that, it signals which point in the network is predestined for resistance enhancing measures, such as mobile flood protection. An extraordinarily high value of A supports the identification of vulnerable elements within a network that would benefit from back-up options, such as emergency generators.

Two characteristics are newly introduced to summarise the behaviour of cascading effects within a CI network: the cascade vulnerability value V describes the vulnerability of end-user elements to be disrupted by cascading effects; the cascade potential value P focuses on the potential of a point element to cause cascading effects.

A (potential) cascade is technically defined as the way back following the connectors from an end-user element (point or polygon) to a starting point (cf. dotted lines in Figure 3-2). A point with A = 0 can be the starting point of a cascade; an element with H = 0 is an end-user element (cf. Table 3-3). The numbers of elements per cascade are defined

Table 3-3: Network characteristics derived from the network configuration.

	Characteristics	Description
Derived Network Characteristics	Hub Value H	Number of outgoing connectors per point element
	Authority Value A	Number of incoming connectors per point element
	Cascade Vulnerability Value V	Number of points cascading a failure to an end-user element
	Cascade Potential Value P	Number of end-user elements disrupted by failure of specific point

as m.

The cascade vulnerability value V is determined per end-user element. For the determination of V all cascades are checked (cf. Figure 3-2). Per cascade j a cascade weight $w_{j,i}$ is determined at each affected point i of the cascade. $w_{j,I}$ depends on the cascade weight $w_{j,i-1}$ of the element before. It is equal to $w_{j,i-1}$ (the cascade weight of the element i-1 before) divided by the number of incoming connections of the same sector $n_{sec,i-1}$ at the element i-1:

$$w_{j,i} = \frac{w_{j,i-1}}{n_{sec,i-1}} \tag{3-1}$$

Equation (3-1) considers redundant connections. The cascade weight $w_{j,o}$ of the end-user element is always defined as 1, required for the determination of the flowing cascade weights $w_{j,i}$. However, it is not used further in the calculation of V. Per cascade j the sum over all cascade weights $w_{j,i}$ of each affected point i is applied:

$$V_j = \sum_{i=1}^{m} w_{j,i} \tag{3-2}$$

If multiple cascades j = 1…n of the same sector are connected to the end-user element the minimum value is relevant:

$$V = \min\,(V_1, V_2 \ldots V_n) \tag{3-3}$$

After an internal sectoral check, an intersectoral check is executed. If multiple cascades j = 1…l of the different sectors are connected to the end-user element the maximum value is relevant:

$$V = \max\,(V_1, V_2 \ldots V_l) \tag{3-4}$$

The *cascade potential value P* is derived for every point i in the CI network, excluding end-user point elements. It counts the potentially disrupted end-user elements in case of failure. P is calculated by the sum at each point i over all $w_{j,i}$ derived from all potential cascades o independent from the sector:

$$P_i = \sum_{j=0}^{o} w_{j,i} \tag{3-5}$$

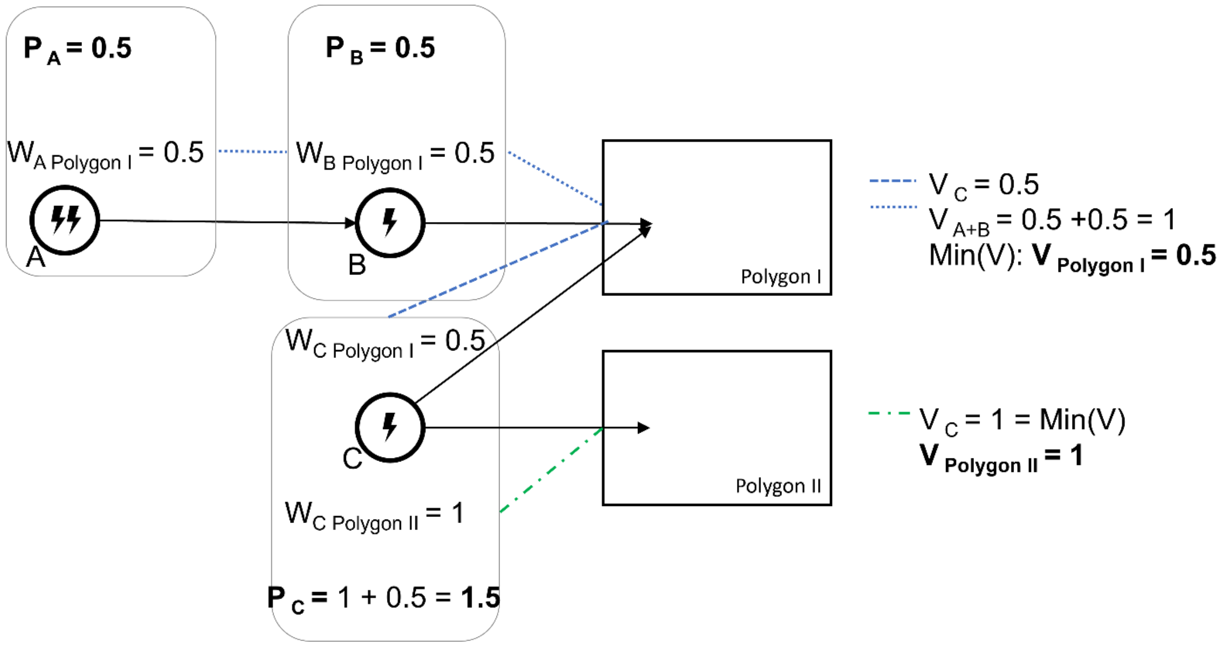


Figure 3-2: The derivation of the cascade vulnerability value *V* for two polygon end-user elements and the determination of cascade potential values *P* for the points A, B and C. The dotted pathways indicate a cascade chain and are connected to their *V* on the right.

3.2.3 Calculation Procedure

The calculation procedure of the CI network module is explained to give an understanding of the CI network's interaction with the simulated flood events and also to show the granularity of the network model. The point elements of the CI network are superposed with the inundated area, in general derived from a 2D hydrodynamic model. The geographic location of the point elements determines the water depth derived from hydrodynamic 2D raster cells. Two calculation modes are available: (1) a steady state calculation of the CI network based on the maximum water depth in the connected hydrodynamic 2D element, and (2) an unsteady state calculation, connecting the water depth for every time step of the hydrodynamic to the point elements. In both cases the maximum (steady state) or the water depth per time step (unsteady state) is compared to the thresholds of every point element. Exceedance of the threshold results in a direct failure state of the point element. The connector elements propagate the failure to the sink point or polygon elements, resulting in a cascading failure without any delay. This indirect failure state can be within the same sector (sectoral failure) or an intersectoral failure or disruption (cf. Figure 3-3). After the specific recovery time of the directly affected point element has passed, functionality—also from the cascading effects—is regained. It is assumed that during the recovery period of a directly affected point element the water depth itself has no further influence on the recovery time.

Several values to quantify the damage to a CI network are conceivable: the number of affected points per sector, the number of people disrupted from CI services per sector $P_{dis,Sec}$ or the disruption time per sector t_{Sec}. A further summarising quantification value is a combination of t_{Sec} [s] and $P_{dis,Sec}$ [people] as suggested by Murdock et al. (2018). This quantification is introduced as the population time $T_{Pop,Sec}$ [people·s] and calculated per CI sector:

$$T_{Pop,Sec} = \sum_{i=0}^{e} P_{dis,Sec,i} \cdot t_i \qquad (3\text{-}6)$$

$T_{Pop,Sec}$ is quantified within the steady state mode. The final flood risk R_{CI} [people·d/a] is calculated as the sum over all hydraulic boundary scenarios n over the product of the damage value, e.g. $T_{Pop,Sec,k}$ [people·d], multiplied by the probability of reoccurrence per hydraulic scenario $p_{hyd,k}$ [1/a]:

$$R_{CI} = \sum_{k=0}^{n} T_{Pop,sec,k} \cdot p_{hyd,k} \qquad (3\text{-}7)$$

Figure 3-3 shows the calculation procedure of the steady state mode for a schematic CI network which is confronted with a flood event, marked with blue wave hatching. The inundation affects the transformer station directly (CI point, sector: energy). The maximum water depth of 1.5 m exceeds the defined water depth threshold of 0.5 m. Starting from the transformer, the failure is propagated to the hospital (sector: health) and the water supply, disrupting CI services for end-users. This is represented by the end-user polygon element I (sector: health; intersectoral disruption) and the end-user polygon element III (sector: water; intersectoral disruption). The disruption of all CI services is determined by the recovery time of 2 d of the directly affected transformer station, as indicated by the stopwatch. The ICT point element is not affected by the disruption due to redundancy of this connector with another point element from the energy sector. The population time per sector is therefore concluded as shown in Figure 3-3. Within the steady state calculation mode, the direct and cascading failures and the time of disruption of the CI services are calculated at once for the whole flooding event. This is mainly required for the damage and risk calculation. In the unsteady state mode, the direct and cascading failures are calculated per time step. These results are suggested for a visualisation of the cascading failure and recovery over time.

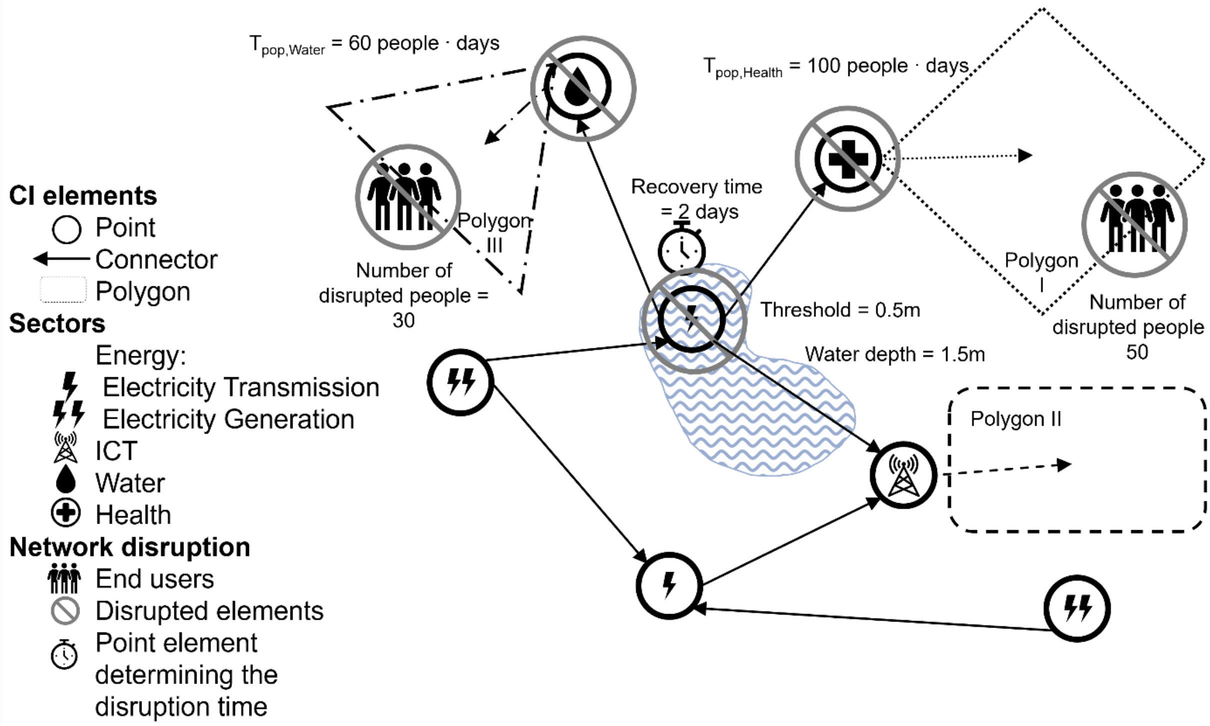


Figure 3-3: Determination of population time T_{Pop} in a representative small network impacted by a flood.

3.3 Implementation and Application of Modelling Approach: Input and Model Setup

After the technical definition of the CI network module, an explanation is provided on how to theoretically utilise the model approach for an application. The CI network module is integrated in the publicly available ProMaIDes software package which consists of range of features for a holistic flood risk analysis (Bachmann, 2012). Plugins for a user-friendly model setup and results visualisation have been developed for QGIS, the open geographical information system (GIS) that is used to prepare the data input and output for the CI network module (Schotten & Bachmann, 2022b).

Figure 3-4 gives an overview of the required input data and the model setup. The first step highlighted in Figure 3-4 is to identify the objective of the CI network model for a potential application area. The intended analysis is often driven by key events of previous flood events, which created awareness of potential cascading effects (de Bruijn et al., 2019). In the next step, it is important to define the boundary for the CI network in relation to the extent of the hydrological and hydrodynamic boundaries of the flood risk analysis. The impacts cascaded through the CI network are expected to exceed the area impacted by the hydraulic event or the river catchment area; this needs consideration when gathering the input data.

Ideally, the input data is compiled from data directly received from the CI operators. However, due to a lack of availability or accessibility other sources must be used. In Figure 3-4, the second step highlights the necessity of collecting point and raster information for the model setup and lists potential data sources. For the identification of point elements in the specific sectors, web mapping services or OpenStreetMap contributors (2017) can provide a basis. To determine the number of end-users, a range of datasets can be used to supply population density datasets (Figure 3-4, step 2) such as the high-resolution data from Meta Data for Good (2022). The point elements and their attributes are defined based on the previous input (Figure 3-4, step 3).

In addition to the input data explained above, data on recovery time is needed, though not easily gathered and almost impossible to obtain from public sources. Thus, it is complemented by findings from empirical studies, as described by Murdock et al. (2018) and Koks et al. (2022). For all types of data need presented in this modelling approach, collaborative CI stakeholder engagement tools are recommended in order to derive more information on the CI network sectors, elements and characteristics (Burzel et al., 2014; de Bruijn et al., 2016, 2018; Murdock et al., 2018).

The data on CI end-users is also not publicly and consistently available for all elements and sectors. To compensate for the lack of data, an alternative is used to determine an estimate for this information. The alternative method is created assuming that point elements deliver their service only to the population closest to them (Pant et al., 2018). Thus, Voronoi polygons are created for all point elements with the same sector and level. To avoid an overestimation of the Voronoi polygons, it must be ensured that there is a row of data surrounding the boundary of the area of interest. The polygon elements are used to derive the number of end-users from raster data (Figure 3-4, step 4). This method also helps the connectors to be assigned in the model itself. It connects source and sink by checking which sink elements are in a source element's closest-distance Voronoi polygon (Figure 3-4, step 5). Figure 3-4, step 6 concludes the technical workflow of the setup of the CI network model by merging the individual elements.

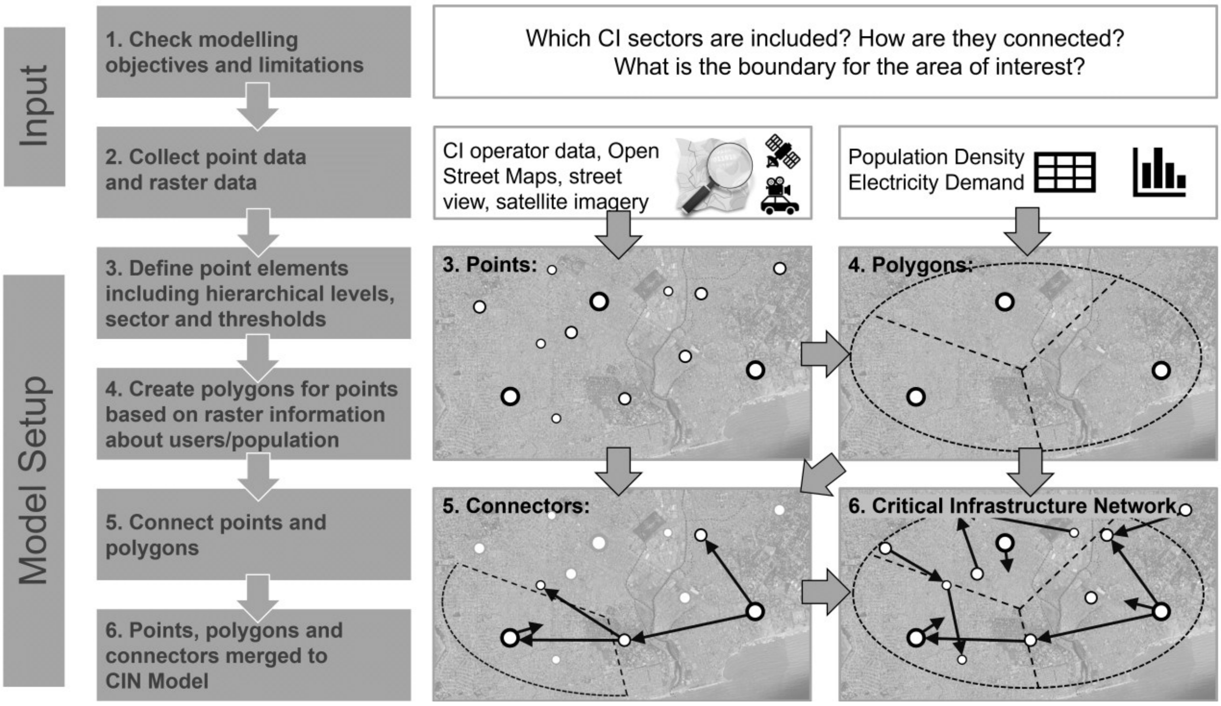


Figure 3-4: Critical infrastructure network module: overview of input and model setup.

3.4 Proof of Concept in Odaw Catchment, Accra, Ghana

In the following section, the CI network modelling approach that has been developed is tested as a proof of concept in a real-world application. The study area is the catchment of the Odaw river in Accra, the capital of Ghana, which frequently experiences flooding in its urban environment (Almoradie et al., 2020; Ntajal et al., 2022). The catchment covers about 271 km² and is located close to the sea (cf. Figure 3-5). The CI network model is part of an existing modelling chain that includes a hydraulic model and flood consequence models for economic damage based on Huizinga et al. (2017) and affected and endangered persons based on (Jonkman, 2007), for an integrated flood risk analysis (Bachmann et al., 2021). For the hydraulic model, a DEM with a 30 m resolution was used and the floodplains were represented by 414000 25 m by 25 m raster cells. Synthetic block rain events of 24 h with three different return periods (T10, T100, T1000) are applied, uniformly distributed over the whole area (Krvavica & Rubinić, 2020).

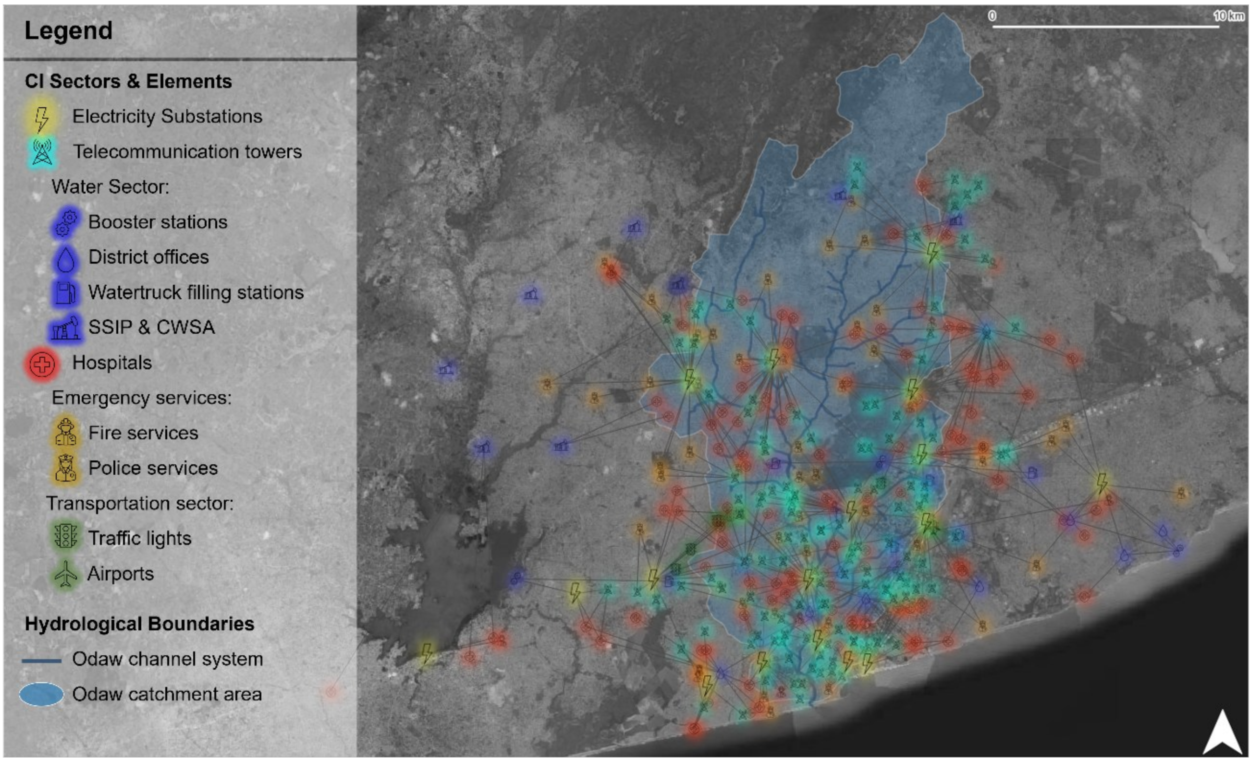


Figure 3-5: Visualisation of all point and connectors in the CI network model of Accra and the Odaw catchment in the background.

3.4.1 Setup of Critical Infrastructure Network Model for Accra

The CI network model itself includes 419 point elements, 472 polygon elements and 1124 connector elements (cf. Figure 3-5). Six different CI sectors are included: energy, water, ICT, health, emergency services and transportation. They are represented by electricity substations, telecommunication towers, water supply facilities, hospitals, fire and police services and logistic point structures such as airports and highway traffic lights. The CI network model's input data exceeds the hydrological catchment boundary of the Odaw river. Thus, modelling of cascading effects beyond the hydrological catchment boundaries is possible.

Table 3-4: Overview of CI element properties used for CI network model in Accra.

Sector	Energy (Electricity)	Information & Communication Technology	Water	Emergency Services	Health
Recovery time [days]	14	7	7	3	7
Waterdepth threshold [m]	0.2	0.2	0.2	0.5	0.4

The location and the CI sector index of the point elements are based on OpenStreetMap contributors (2017), complemented with data from web mapping services. Every point element is accompanied by a polygon to mark the area of influence on other sink point elements for the definition of connectors. For CI end-user polygons, the polygon is also used to derive the number of end-users from a population density dataset (Meta - Data for Good, 2023) . Due to a lack of more specific datasets from CI operators, Voronoi polygons are used to mark the areas of closest distance to the source point element, as described previously. In the transportation sector, point elements are end-user elements given the attribute of end-users derived from historic traffic and passenger numbers.

A stakeholder workshop with local CI operators was held to validate the present input and to add additional relevant point elements. The workshop was also used to confirm the CI element properties such as recovery time and water depth threshold with experts from the field of CI operation and crisis response (cf. Table 3-4) as well as to identify the sectors' dependencies that should be highlighted with connector elements. The workshop discussion was accompanied by a schematic representation of the network shown in Figure 3-6 (Deltares, 2021). It features all integrated CI sectors of the CI network model as well as the civil population. Figure 3-6 also shows which sectors have depend-

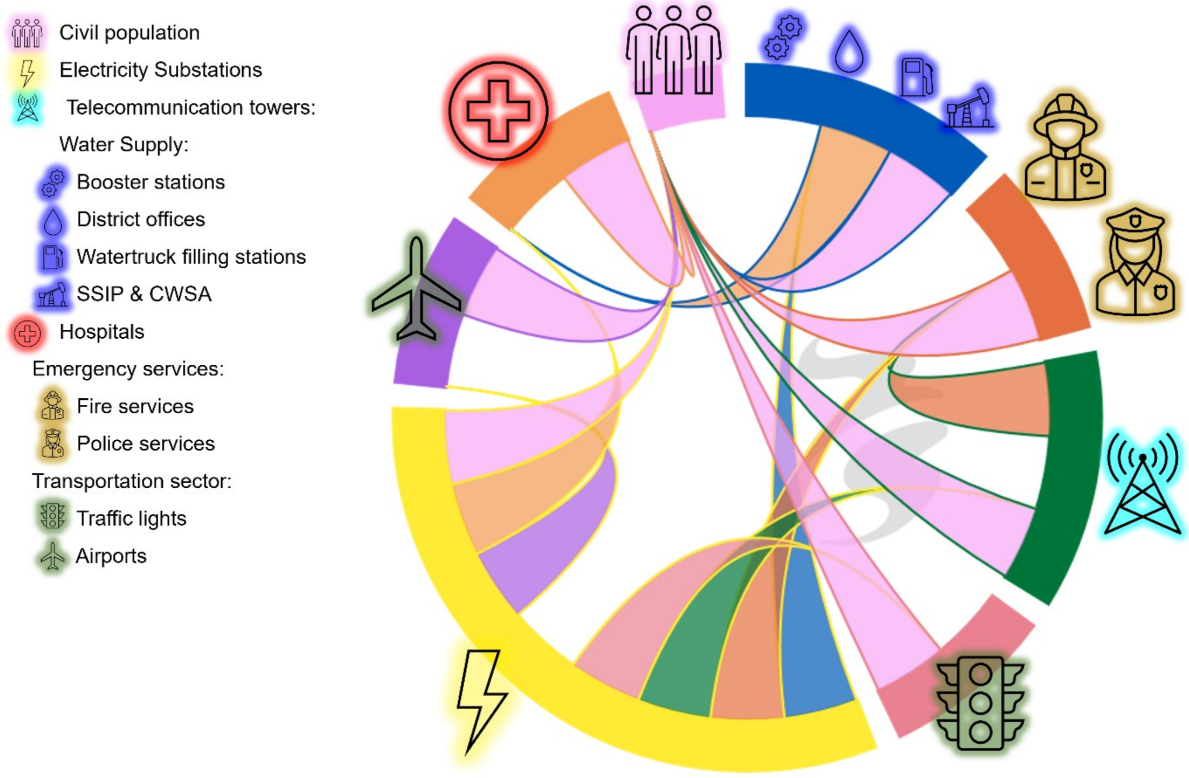


Figure 3-6: Intersectoral connections displayed with circular segments and circular triangles pointing from source to sink sectors, generated with Deltares CIrcle web tool (Deltares, 2021).

encies and are linked through connector elements.

Stakeholder engagement methods like the CIrcle method provide a good discussion platform for CI stakeholders to build a community and enable discussion about the identification of CI sectors, their interdependencies and missing information for the CI network modelling and risk management objectives (Burzel et al., 2014; de Bruijn et al., 2016, 2018; Murdock et al., 2018)

3.4.2 Specific Setup of Water Sector

During the workshop interaction, specific sectors were discussed and differentiated more extensively. This proof of concept is used to demonstrate that the findings of these discussions on the water sector can be accommodated within the modelling approach of the CI network module. The representation of the energy, ICT, emergency services and transportation sectors is derived from the standard setup approach described previously. Representing the fresh water supply sector and its physical system is a stress test for the CI network modelling method.

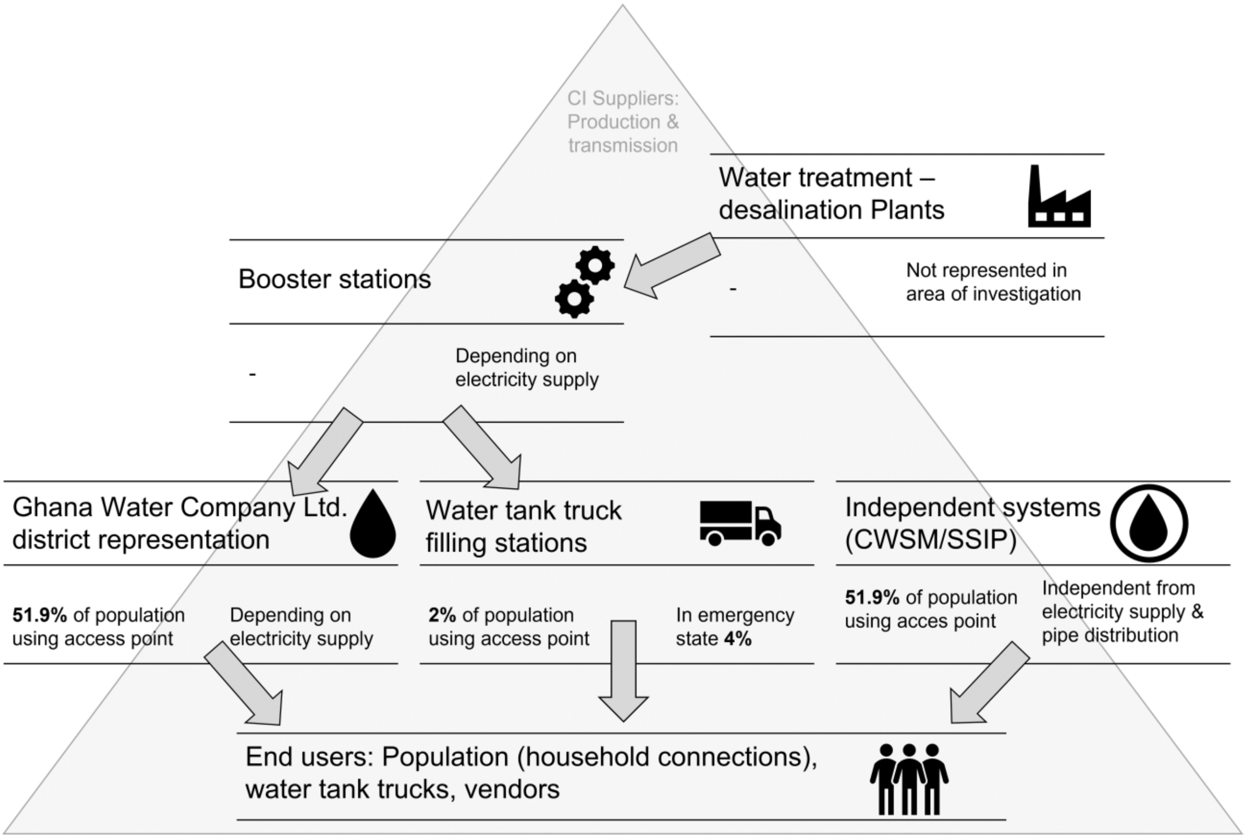


Figure 3-7: Water sector represented in the CI network model of the Odaw Catchment, Accra, Ghana (Adank et al., 2011).

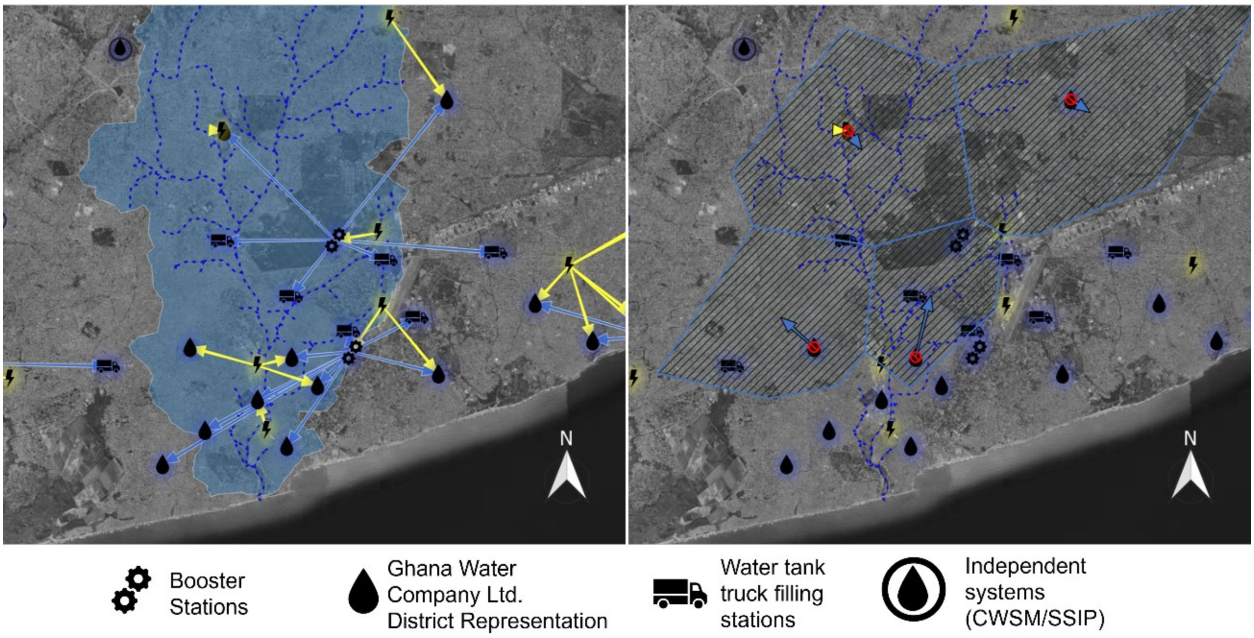


Figure 3-8: Left: Water sector network including dependencies on energy sector elements within the Odaw river and catchment displayed in the background. Right: Impacted point and polygon elements from the water sector.

The water sector is represented by different types of supply elements with specific dependencies, as shown in Figure 3-7. Forming the backbone of the supply are water treatment and desalination plants. Booster stations within the area ensure there is sufficient pressure in the water pipes from treatment and desalination plants to the household level (Adank et al., 2011). They form the highest level in the hierarchy of the CI network models' water supply sector. Connected to the supply of the booster stations are the district offices and the water tank hydrants. The water tank hydrants fill up the water tank trucks that deliver water to households. The percentage of the population connected to the pipe-based distribution system and the water tank truck-based distribution can be seen in Figure 3-7. These percentages are multiplied by the total number of potential end-users in the Voronoi polygons of end-user polygons: end-user suppliers are the district representations, water tank truck hydrants and the small-scale independent providers (SSIP) and community managed small town water systems (CMWS). The SSIP and the CMWS operate outside of the normal water supply network and do not depend on the booster stations.

The water tank trucks and their supply through hydrants are assumed to be able to switch their operation mode to an emergency state and raise their capacities. This emergency mode only activates once a connected structure is disrupted. The emergency mode is not operable if higher level point elements like the booster stations are affected. Due to a lack of available data, the modelling of the water supply structure ignores the supply via other private water companies besides the SSIP and the CWSM, as well as freshwater consumption via vendors and kiosks. No data was available on the role of Ghana Water Company district representations, so it was assumed to have a technical function within the supply system.

Figure 3-8, left-hand image shows a filtered version of the CI network model that highlights the water supply structures mentioned above, the connected energy sector point elements and the Odaw river system and its catchment. After superposing the CI network model with hydraulic modelling results, the disruption of the system is derived. Figure 3-8, right-hand image shows the polygons affected. The comparison of both images in Figure 3-8 shows that the area of impacted CI users exceeds the catchment area.

3.4.3 Network Characteristics

An analysis of the CI network characteristics gives an overview of the potential disruption of the CI network if triggered by an external impact. To get an understanding of the network, network characteristics are briefly analysed. Figure 3-9 highlights the point elements in the CI network with cascade potential values P (cf. Section 3.2.2) bigger than 10. These point elements are all associated with the included primary CI sectors: energy, ICT and water. The point element with $P = 95$ is an electricity station located about 200 m from the Odaw river. It gives an indication for further investigation and potential mitigation measures before the combination with the modelled inundations.

The outstanding network characteristics give additional information about vulnerable point elements and potential cascades. Table 3-5 summarises the minimum and maximum values of the introduced network characteristics and provides an understanding of the representation of the sectors in the CI network. Extensive analysis of the network characteristics is mainly of interest for mitigation measure planning and is outside the scope of the work presented in this paper.

Table 3-5: Minimum and maximum value of all introduced network characteristics per CI sector.

Sector	**Authority Value *A***		**Hub Value *H***		**Cascade Potential Value *P***		**Cascade Vulnerability Value *V***	
	Min	Max	Min	Max	Min	Max	Min	Max
Energy	0	1	0	45	5.7	115.75	1	1
Water	0	2	0	20	1	64	0	4
Information and Communication Technology	1	1	0	8	1	8.61	2	2
Health	1	22	0	3	1	1	2	4
Emergency Services	1	3	0	1	1	1	2	8

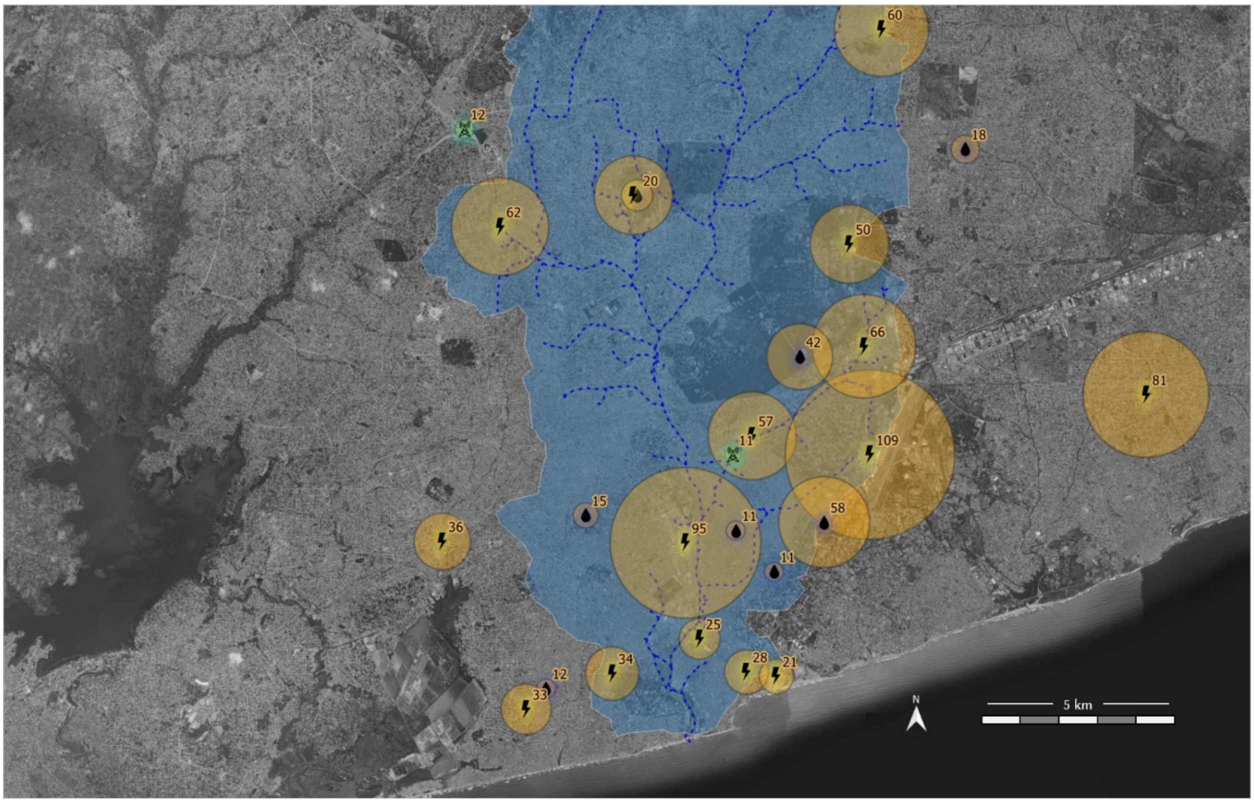


Figure 3-9: Point elements in the CI network model of Accra with cascade potential values *P* > 10 featuring the energy, ICT and water sectors. 1 km radius equals a cascade potential value *P* = 50.

3.4.4 Results

Different types of output can be generated from the CI network model. One type of output is the spatial datasets resulting from the steady state calculation mode (cf. Section 3.2.3). From the unsteady state calculation mode, spatial data is available for every time step. Figure 10 shows the catchment of the Odaw, highlighting a different aspect of the CI network model in each quadrant. The quadrants show how to superpose the results of a hydraulic model run with the input (B, D) and output (A, C) of the CI network model. In part (D) of the image, the hydraulic model and the main channel of the investigated Odaw river are shown superposed with energy sectors' point elements and the associated polygon elements. Part (B) connects the energy sector's points with the ICT sector's points. The polygons show the area supplied with mobile network connectivity.

Part (A) highlights the effect of flooding on the structures shown in part (B). Energy and ICT sector points that are directly or indirectly disrupted are marked with a red circle and the polygons from the ICT sector are hatched in black. Part (C) shows the equivalent of the health and energy sector.

Table 3-6: Flood risk matrix combining classic flood damage in bright grey and CI network consequences in white measured by population time.

	Annuality [a]	HQ10	HQ100	HQ1000	Risk *R* [... / a]
	Probability of reoccurence p_{hyd} [-]	0.145	0.0495	0.0055	
Classic flood consequences C	Economic damage [USD]	295.71 Mio.	465.83 Mio.	631.01 Mio.	**69.41 Mio.**
	Affected [people]	1.12 Mio.	1.3 Mio.	1.49 Mio.	**234 618**
	Vulnerable [people]	12 688	20 099	34 510	**3 024**
Population Time T_{Pop} per CI Sector	Energy [people x days]	2.23 Mio.	8.1 Mio.	9.53 Mio.	**776 546**
	Water [people x days]	1.61 Mio.	1.61 Mio.	2.43 Mio.	**326 465**
	Emergency services [people x days]	1.53 Mio.	13.16 Mio.	16.53 Mio.	**964 744**
	Information and communication technology [people x days]	2.03 Mio.	6.15 Mio.	7.47 Mio.	**640 264**
	Health Care [people x days]	3.15 Mio.	7.79 Mio.	11. Mio.	**903 260**
	CI risk sum [people x days]	10.56 Mio.	36.8 Mio.	46.95 Mio.	**3 611 279**

Information for decision makers is presentable in maps to provide accessibility to the spatial extent of consequences for the CI network, comparable to the quadrants of Figure 3-10. Specific filters in geoinformation systems enable the visualisation of the output

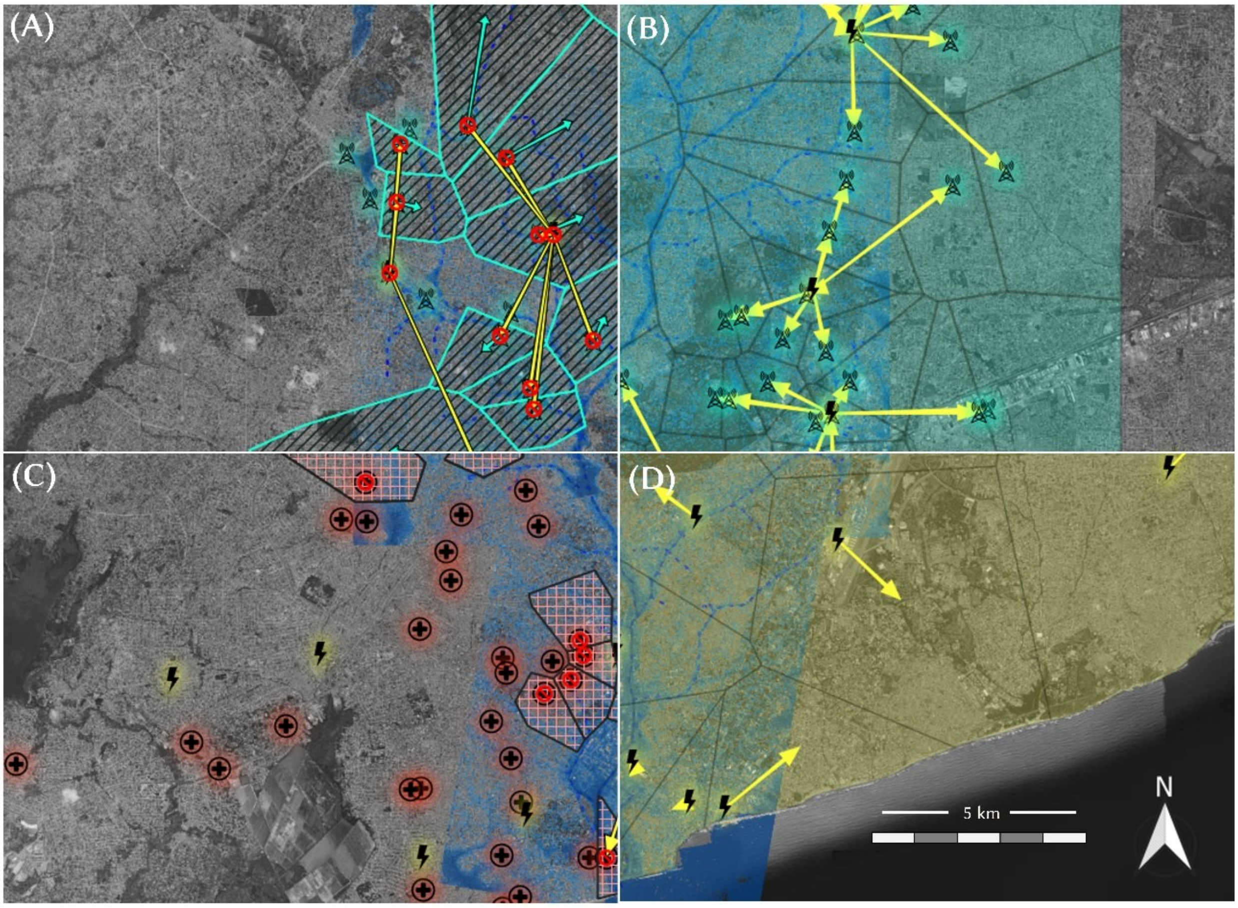


Figure 3-10: View of the Odaw catchment with four quadrants highlighting various aspects of the CI network model: (A) highlights the impacted ICT point elements, their associated disrupted polygons and the energy sector points. (B) shows the input for the ICT sector and the connection to energy points. (C) shows disrupted health sector elements and associated polygons. (D) shows the input point and polygon elements of the energy sector.

data for the sectors of interest. The full spectrum of generated data superposed is not helpful for decision makers in flood risk management or CI operations.

Another type of information output is the summary of the consequences per flood event and, ultimately, the total flood risks in the flood risk matrix (cf. Table 3-6). The flood risk matrix shows the annuality of the three flood events and their derived probability of reoccurrence p_{hyd}. In addition to the established categories of consequences C, such as economic damage or consequences for people, it also summarises the population time T_{Pop} (cf. Equation 3-6) per sector. The resulting risk $R_{CI\,sec}$ (cf. Equation 3-7) is calculated per category and is listed in the last column. The last line shows the overall CI risk sum R_{CI} for the complete CI network. With the CI consequences, a new dimension is added to the flood risk matrix.

3.5 Discussion and Outlook

The technical approach to modelling CI networks presented here is required for flood risk management procedures, as proposed by (Burzel et al., 2014) and Schotten & Bachmann (2023). The challenge of this type of analysis is more organisational than technical, however. Responsibilities for flood risk adaptation of CI are split across several stakeholders, e.g. CI operators from a wide range of sectors or public authorities. To tackle this challenge, the consistent participation of CI stakeholders is highly recommended.

The CI network modelling approach represents the real CI network based on logical and physical dependencies of the CI elements. Empirical approaches were used to derive additional information about the CI network as well as its elements and attributes. The modelling approach itself was tested and verified by simple, synthetic models representing different aspects of network characteristics (e.g. linear, split or circular networks). Within the modelling approach, several technical assumptions are made: the state of a CI element is defined as functional or disrupted without any intermediate states; the recovery time is started once the water depth threshold is crossed even though the CI element might still be inundated. These technical assumptions will not always reflect real conditions and must be communicated. However, for flood mitigation planning on a regional scale these assumptions are rated as suitable, but for a detailed network performance analysis they may be too limited.

The main purpose of the presented proof of concept in Accra is to demonstrate the approach itself and its capabilities. The model’s uncertainties arise mainly from two factors. Firstly, uncertainties are caused by the raw input data itself (e.g. localisation, extent of the structure itself and dependencies of the CI elements, recovery times, water depth threshold values, number of end-users per polygon). To rate the introduced level of uncertainty, a sensitivity analysis concerning these parameters is recommended. The second cause of uncertainty is the transformation of the raw data into model input data, e.g. the use of Voronoi polygons as a nearest-neighbour assumption for the connection of CI elements. Both types of uncertainties could be significantly reduced if more intense use could be made of direct and sensitive network information (often available from the CI providers). New potential procedures enabling this option would be, for example, the anonymisation of CI end-user data preventing privacy issues or the derivation of data from information shared during CI operator participations.

Validation of the model with data from a real flood event is a priority in the future. In the presented proof of concept, only plausibility checks of data and model results with local stakeholders were performed. However, the challenge remains to acquire reliable validation data, especially in environments with scarce data, such as Accra. Complex datasets for flood events, related cascading effects, CI failures and disruption of CI services are currently not available due to a lack of awareness and inconclusive responsibilities. In the future, it is recommended to authorities to collect and share this information or at least encourage local news agencies to do so. However, it must be stated that the physical and logical character of the approach reduces the requirement for validation.

3.6 Conclusion

The CI network modelling module is presented in this study as a new CI network modelling approach for the quantification of multisectoral CI service disruption on a regional scale by flood events. It combines high-level architecture with a network topology-based approach. Multisectoral CI networks are modelled with three types of CI elements: points, polygons and connectors. The relation to CI end-users is established in the model by sectoral and intersectoral dependencies.

In addition to established CI network characteristics like the hub value H and authority value A, two new key figures have been introduced. The cascade vulnerability value *V* shows the vulnerability of a CI end-user polygon. The cascade potential value P helps to identify point elements with high potential for disruption within a cascade, leading to cascading failures.

When virtually confronted with flooding scenarios, the CI network model shows direct disruptions and also indirect disruptions within a sector and on an intersectoral level through cascading effects. It summarises CI service disruption quantitatively by the number of disrupted CI end-users, the time of their disruption or the product of the two, introduced as the population time T_{Pop}. Results for each time step of the CI networks' interaction with the flood model can help the cascading behaviour to be understood.

The CI network model is adaptable to the precision of the available data coverage and specific stakeholder interests. The simple structure of three CI elements is applicable from a simple design with few elements to a complex multisectoral multi-layer model. It is suited for applications driven by publicly available data sources, by specific and complex datasets or by qualitative information from CI operators and other stakeholders. This modelling approach balances the level of detail the CI model replicates real CI networks and the detail necessary for an improved flood risk management. The approach provides a basis for the interaction of flood risk managers and a multisectoral group of CI operators on a regional scale.

The CI network modelling approach is proven in a proof of concept for the Odaw catchment in Accra, using data from publicly available data sources and complemented and validated through individual and participatory CI stakeholder engagement. A flood risk matrix is derived in which CI disruptions are quantified in addition to usual flood consequences. Additionally, it is proven that CI disruptions can exceed the catchment area of the Odaw river. All in all, a range of possibilities for flood risk analysis has been defined through the CI network module. Opportunities are enabled to integrate CI networks and their disruptions into flood risk management procedures.

4 CATALOGUING AND TESTING FLOOD RISK MANAGEMENT MEASURES TO INCREASE THE RESILIENCE OF CRITICAL INFRASTRUCTURE NETWORKS

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Smart Cities 2024, 7(5), 2995-3021

DOI: 10.3390/smartcities7050117

Critical infrastructure (CI) networks face diverse natural hazards, such as flooding. CI network modelling methods are used to evaluate these hazards, enabling the analysis of cascading effects, flood risk and potential flood risk reduction measures. However, there is a lack of linkage between analytical methods and potential multi-sectoral, structural, and non-structural measures. This deficiency impedes the development of CI network (CIN) models as robust tools for active flood risk management. CI operators have significant expertise in managing and implementing flooding-related measures within their sectors. The objective of this study is to bridge the gap between the application of CIN modelling and the consideration of flood measures in three steps. The first step is conducting literature review and CI stakeholder interviews in Central Europe on flood measures. The second step is the culmination of the findings in a comprehensive catalogue detailing flood measures tailored to five CI sectors, with a generalized category spanning each phase of the disaster risk management cycle. The third step is the validation of the catalogue's utility in a proof-of-concept study along the Vicht River in Western Germany with a model-based flood risk analysis of five flood measures. The application of the flood measure catalogue im-

proves the options available for active and residual flood risk management. Additionally, the CI flood risk modelling approach presented here allows for consideration of disruption duration and recovery capability, thus linking the concept of risk and resilience.

4.1 Introduction

Infrastructure and organizations supplying essential services to society are described as critical infrastructure (CI) or critical entities. In an environment with a changing climate, extreme weather events cause more frequent or extreme flooding events that disrupt CI (UNDRR, 2021). CIs are organized in sectors such as electricity, information and communication technology (ICT), freshwater supply, sewage water treatment, and gas supply. These form networks through their dependencies (Rinaldi et al., 2001). Disruptions to individual CI elements caused by flooding cascade through these dependencies both within CI sectors and outside these sectors (Fekete, 2019). These effects are referred to as cascading effects and are characteristic of the arrangement of CI sectors in networks or critical infrastructure networks (CIN).

A generalized flood risk management (FRM) workflow consists of three elements: analysis, assessment, and action-taking (Schotten & Bachmann, 2023b). In this framework, the flood risk is defined as the product of flood consequences as well as the probability of their occurrence (Klijn et al., 2015). The flood consequences can include several dimensions of consequences such as the economic damages, the consequences for the population affected or endangered or the consequences for the critical infrastructure services (Schotten & Bachmann, 2023b). To analyse and assess the risk to CIN caused by flooding and other natural hazards, network modelling techniques are utilised to assess the highly complex interactions in closely webbed networks (He & Cha, 2018; Mühlhofer et al., 2023; Pant et al., 2018). Depending on their design, modelling approaches allow consideration of the characteristics of individual CI sectors, of direct disruptions caused by flooding, and of indirect disruptions caused within a sector (sectoral) and across multiple sectors (transsectoral). These effects are referred to as cascading effects and can be quantified as time of disruption per person, as demonstrated in the study conducted by Murdock et al. (2018) and Schotten & Bachmann (2023a). A range of network modelling approaches are available, and a handful of them also focus on flood consequences, but these modelling approaches rarely concentrate on the testing and implementation of flood measures.

After determining the flood risk for the CI, an assessment is conducted. This requires public or political representatives to decide on the acceptance or refusal of a current flood risk situation. Acceptance involves dealing with residual flood risk and defining preparation, response, and recovery measures to address the remaining risk. The refusal of flood risk situations leads to the development of prevention and mitigation measures to invoke changes (Bachmann, 2012). Case studies analysing flood risk for CIN often overlook potential measures or fail to assess the potential benefits of measures in their modelling frameworks (Ani et al., 2019). CIN, by their definition, overarch different CI sectors; thus, knowledge of the specific CI sectors is necessary in order to include appropriate measures. Another challenge is that conventional flood risk adaptation does not consider measures embedded in an interdependent supply network of CI, which necessitates a systematic understanding of potential measures. Additionally, input and validation data are scarce and limit not only the analysis, but also the inclusion of potential measures (Ramachandran et al., 2016; Schotten et al., 2024).

Measures vary according to each stage of the disaster risk reduction (DRR) management cycle. In the context of this work and considering CI as a thematic background, five stages of the DRR cycle are defined, in accordance with the German Federal Office of Civil Protection and Disaster Assistance (BBK) (2023) and the study conducted by Petit et al. (2013). These stages define time periods in the progression of actions necessary after a disaster event or, as defined here, *impact*. The next stage is defined as *response*, describing the actions or strategies that respond and adapt immediately to the adverse impacts of an event. Subsequently, the stage of *recovery and rehabilitation* is highlighted, focusing on returning CI services to acceptable and constant conditions for end users and chain partners. The stage of *prevention and mitigation* progresses to increase resistance, adapt to the impact, or avert in other ways. The final stage before closing the DRR management cycle describes the *preparation* during which all measures are taken in the immediate anticipation of an event (cf. Figure 4-1). Further, all measures in the DRR management cycle for flooding are referred to as flood measures.

The consideration of measures is what differentiates the term risk from the term resilience. (Peterson St-Laurent et al., 2021) define resilience as the “capacity of a system to return to desired conditions after disturbance”, which not only includes the capacity itself but also the time until a system is returned to a desired state. This definition of resilience is applied in this manuscript, as also applied by (Gourbesville & Batica, 2014). The Sendai Framework’s definition states that systems are able to react more resiliently to disruptions if they are equipped to “build back better” after disruptions (United Nations, 2015).

Cataloguing of flood measures has been frequently used by homeowners at property level to increase the resilience of properties (Attems et al., 2020; Meyer & Hartmann, 2023). Previous events and the experiences of CI operators and stakeholders can also be used to catalogue measures taken. (de Bruijn et al., 2019) identified measures for a case study in a participatory environment with CI operators and compared the numbers of people and duration of disruption with and without measures. Sector-specific associations, such as the German Association for Water, Wastewater and Waste (DWA) and the German Technical and Scientific Association for Gas and Water (DVGW), take a normative approach to measure collection by defining technical recommendations to manage flood risk for the operators of their supply networks. The study by (Azevedo de Almeida

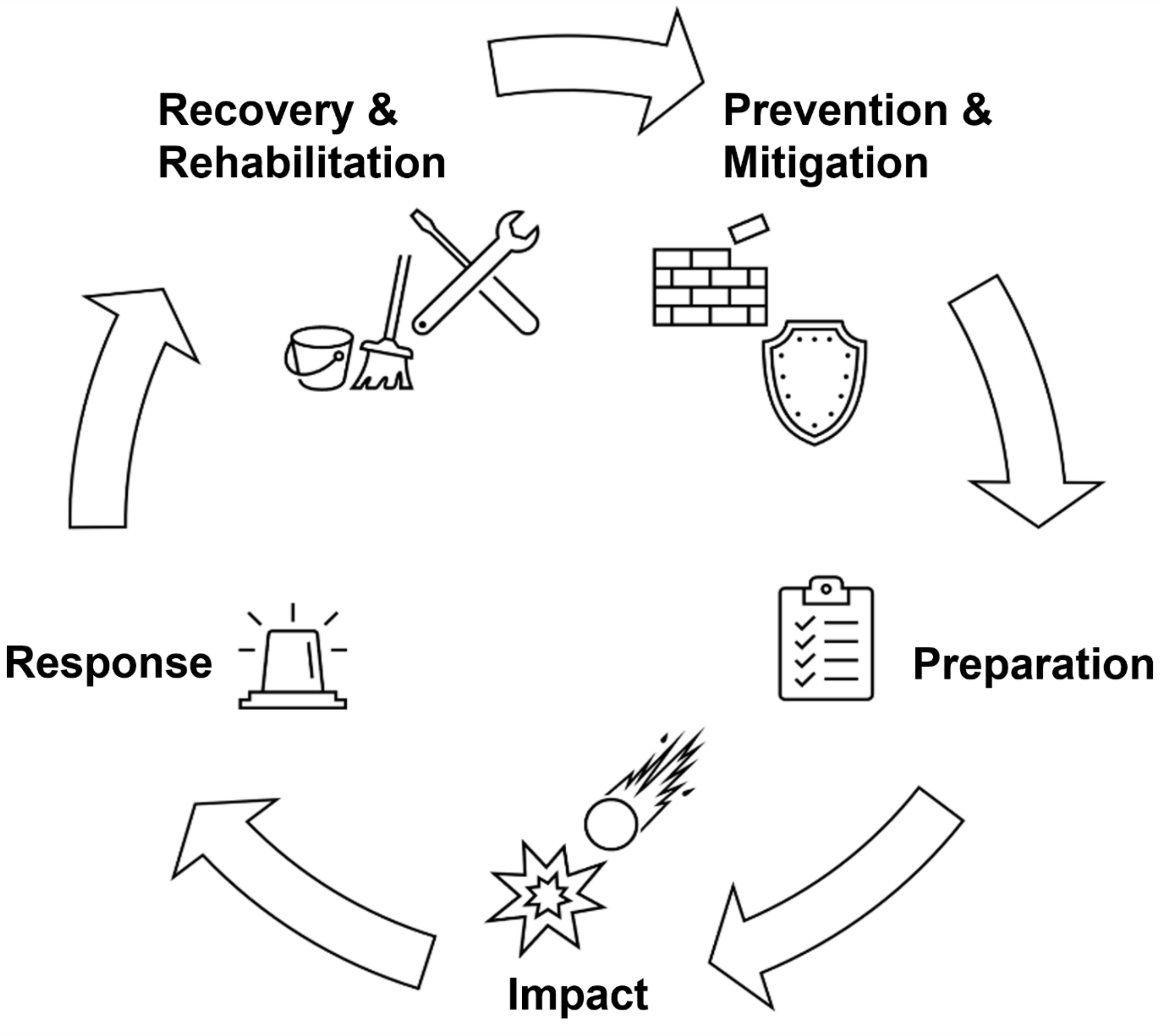


Figure 4-1: Disaster risk management cycle as suggested by the German Federal Office of Civil Protection and Disaster Assistance (BBK).

& Mostafavi, 2016) concentrated on seven measures across three CI sectors to increase resilience with respect to sea level rise. However, conventional measures, such as linear protection structures, have been tested in the hydraulic domain and chosen based on their effect on CI networks (Vamvakeridou-Lyroudia et al., 2020). Conventional flood protection, mitigation or recovery measures not considering CI – as gathered in other studies (Kreibich et al., 2015; Lendering et al., 2015) – are not the focus of this study. Flood measures have been collected systematically previously in research manuscripts and practice, but what is currently missing is a collection of flood measures specific to CI.

In summary, the current literature reveals a significant gap between FRM and CI, indicating a need for closer integration. CIN modelling methods are inadequately aligned with the objective of evaluating flood measures. Additionally, there is a lack of systematic collection of flood measures across CI sectors for this purpose.

To address these gaps, it is essential to establish a comprehensive integration between FRM and CI, considering both technical and organizational aspects. The current state-of-the-art risk-based evaluation of measures must be expanded to incorporate those from the CI domain. This requires the structural definition of measures, categorized by CI sectors and specified by their implementation timelines.

In the present study, the focus is on sectors with a high level of physical and logical interdependencies, such as electricity, ICT, freshwater supply, sewage water treatment, and gas supply. These are referred to as primary sectors because of their high potential to disrupt other sectors. Secondary sectors, which are defined by their characteristics of mostly relying on incoming physical and logistical dependencies and severity for the civil population, are excluded (e.g. health or public administration). Additionally, the transportation sector and linear structures of the previously highlighted sectors, such as pipes, cables, and road networks, were not specifically considered.

The present work has already provided an introduction covering the thematic background, current knowledge gaps, and the first part of a literature study on critical infrastructure protection and adaptation measures. The objective of this manuscript to bridge the gap in between CIN modelling for FRM and the consideration of flood risk reduction measures is addressed in two chapters: Section 4.2. describes the systematic collection of flood measures through a second, systematic part of the literature review, expert interviews and a third part of the literature study based on the input of the interviews. The findings of this chapter funnel into a measure catalogue for each CI sector, as well as a generalized category and for every stage of the DRR management cycle. In the following chapter (cf. Section 4.3), a flood risk management approach including CIN modelling methods is introduced to enable a risk-based evaluation of potential flood measures. Subsequently, a case study is presented in Section 4.4 for the low-mountain range stream Vicht near Stolberg, Germany. A flood risk analysis is conducted utilizing a CIN model, together with an assessment of the effectiveness of measures taken from the catalogue to reduce flood risk. In the subsequent chapter, the findings of this study are discussed, and an outlook is provided for potential future developments and challenges. Finally, the presented work is concluded.

4.2 Flood Measures for Critical Infrastructure Networks

Flood measures specific to critical infrastructures are catalogued in this chapter using literature and expert interviews as sources. The methodology used to conduct the interviews, and the derivation of the catalogue are briefly described. Generalised CI measures are deducted from sector-specific CI measures with equivalent approaches. Subsequently, the results for each CI sector are clarified individually.

4.2.1 Methodology for the Derivation of a Measure Catalogue

The catalogue, literature review, and interviews are structured along the stages of the DRR management cycle previously introduced: impact, response, recovery and rehabilitation, prevention and mitigation, and prevention (cf. Figure 4-1). The hierarchical structure of each CI sector as well as the idealised elements are outlined to fully understand the impact and subsequent steps of the DRR management cycle. The identification of each CI sectors measures is done in a three-step process: (1) Systematic literature study on CI sector elements and hierarchical structure. (2) Validation and detailed elaboration of the hierarchy and measures in the interviews. (3) Complementation through a second literature review.

The first step – an initial systematic literature study, is carried out to identify CI elements and hierarchical structures across primary CI sectors. The systematic literature review examined the results for the term ‘critical infrastructure hierarchy’ and was complemented by the terms ‘measures’, ‘natural hazards’, and ‘flooding’ on a scientific search engine. In a subsequent step, the ‘electricity’, ‘ICT’, ‘freshwater’, ‘gas’, and ‘wastewater’ sectors were added as a word to the search term. These sectors were selected for further analysis due to their alignment with the selected modelling method from Schotten & Bachmann (2023a).

Relevant literature defining CI sector hierarchies and potential measures was considered prior to conducting interviews. This included publications and reports on sectoral damage and adaptation studies (Anakhov et al., 2020; Fröbel, 2003; Wricke et al., 2003), multi-sectoral studies on network and protection measures (Kong et al., 2021; Kühne, 2022) as well as recommendations from public authorities (German Federal Ministry for Housing, Urban Development, and Building (BMWSB), 2022; German Federal Ministry of the Interior (BMI), 2011; German Federal Office for Civil Protection and Disaster Assistance (BBK), 2019; German Federal Office of Civil Protection and Disaster Assistance (BBK), 2023).

Table 4-1: Interview partners for the compilations of flood risk measures specific to critical infrastructures. The X indicates the affiliation with certain sectors.

	Interviewee's occupation	**Sector of expertise**					
		Electricity	**ICT**	**Freshwater**	**Wastewater**	**Gas**	**Other**
1*	Technical director of a regional drinking water supply company			X			
2*	Managing director of the municipal utilities	X	X	X			
3*	Managing director of the municipal utilities	X	X	X			
4	Expert at the state ministry for energy supervision and energy regulation	X				X	X
5	Board member in an association of critical infrastructure operators	X		X		X	X
6	Independent international blackout and crisis preparedness expert	X					X
7	Professor of electrical engineering with a focus on cable networks		X				
8*	Leader of the disaster management team of a telecommunications provider		X				
9*	Expert in system operations and the crisis Management Framework for a regional electricity, gas, and telecommunications network operator	X	X	X			
10*	Team leader for network planning in a wastewater collection and treatment company				X		
*With experience in flood events							

In the second step, interviews are conducted to validate the findings from the first step and complement the understanding of the hierarchical network systems for five CI sectors (electricity, ICT, freshwater, gas, and wastewater). Once the network system has been validated with the interviewees, potential flood risk reduction measures or literature pointing towards additional measures are identified. The interviewees are international experts and operators in the field of CI operations and flood risk management in Central Europe. Therefore, the measures collected are most applicable in industrialized environments. Table 4-1 provides an overview of the occupations of the interviewees and asterisks are used to indicate who has practical experience in managing flooding. The interview methodology follows Gläser and Laudel (2010) and is integrated into the presented study, following the approach taken by to Folkens, Bachmann, and Schneider (2023). The interviewees are presented with four questions structuring the conversation: (1) Which elements of the hierarchy in the CI sector are vulnerable to flooding? (2) What is the structure of the critical infrastructure sector? (3) Which options are available for a specific sector as flood management measures? (4) Is it possible to quantify the effects of these measures? As an outcome of the interviews, a hierarchical network structure is presented for each sector along with the measures that were identified and described. Other statements made by interviewees are considered briefly during the discussion of this manuscript (cf. Section 4.4).

In the third step of compiling a catalogue of measures, additional measures were gathered based on the literature recommendations from the interviewees. This literature study focused on guidelines and reports from critical infrastructure operators (Assmann et al., 2013; German Association for Water, Wastewater and Waste (DWA), 2013; German Technical and Scientific Association for Gas and Water (DVGW), 2017).

As a result of all three steps outlined above, a hierarchical structure for each sector is identified in Figure 4-2. Another result is the measure catalogue presented in Appendix 1 showing the possible impacts as well as the measures identified throughout the literature study. The catalogue does not describe the continuous development of the measures catalogue from steps 1 to 3 to keep the results section clear and concise. A range of measures or measure types occurs in every sector and is thus summarised as generalized measures in the following Section 4.2.2. For each individual sector, a hierarchical system is introduced and one measure from Appendix 1 is focused on as an example.

The objective of this study is not to replicate the hierarchical structure and granularity of each CI sector as precisely as possible but to do so at the level of detail necessary to comprehend the influence of the measures on the network as a whole. The knowledge of CI operators plays a pivotal role in understanding, safeguarding and managing CI assets during extreme events. Therefore, interviews with CI operators are conducted to confirm and complement the hierarchical structures across various CI sectors and the potential impacts on the relevant CI network elements, and to identify measures for each step of the DRR management cycle.

4.2.2 Generalised Measures

Generalised measures are introduced for each stage of the DRR management cycle. Before elaborating on the DRR management stages that link to the measures, it is important to understand the dynamics of the flood impacts:

Impact: Across all sectors, inundations disrupt punctual assets and impact CI services. However, the impacts on electricity and wastewater treatment facilities are exceptional because these facilities present immediate health risks when impacted. Most operators do not focus on damage to linear structures for risk management or identification of potential measures during the interview.

Response: Network replacement units (NRU) are of the highest importance to all sectors and play a key role in the response to flooding events. NRUs refer to the different types of services that they replace (e.g. generators, pumps, or ICT components). In addition to the availability of NRUs, sufficient availability of fuel and the possibility of connecting NRUs to CI structures are important to all sectors. The NRUs significantly reduce the response and recovery times. Regional social networks of critical infrastructure operators inform each other about the availability and needs of the NRUs' systems and fuel reserves. Another point mentioned by experts from all sectors is that technical maintenance teams gather at predefined locations during disruptive events to receive and follow up on action and priority lists. The availability of a priority list of measures to be taken by each CI operator during the response phase is connected to the previous two measures.

Recovery and Rehabilitation: The last point referring to priority lists of the response phase mentioned above also applies to the recovery and rehabilitation phase. In addition, the generalized measures in this stage refer to the restoration of the CIN networks' functionality and the dismantling of the NRU.

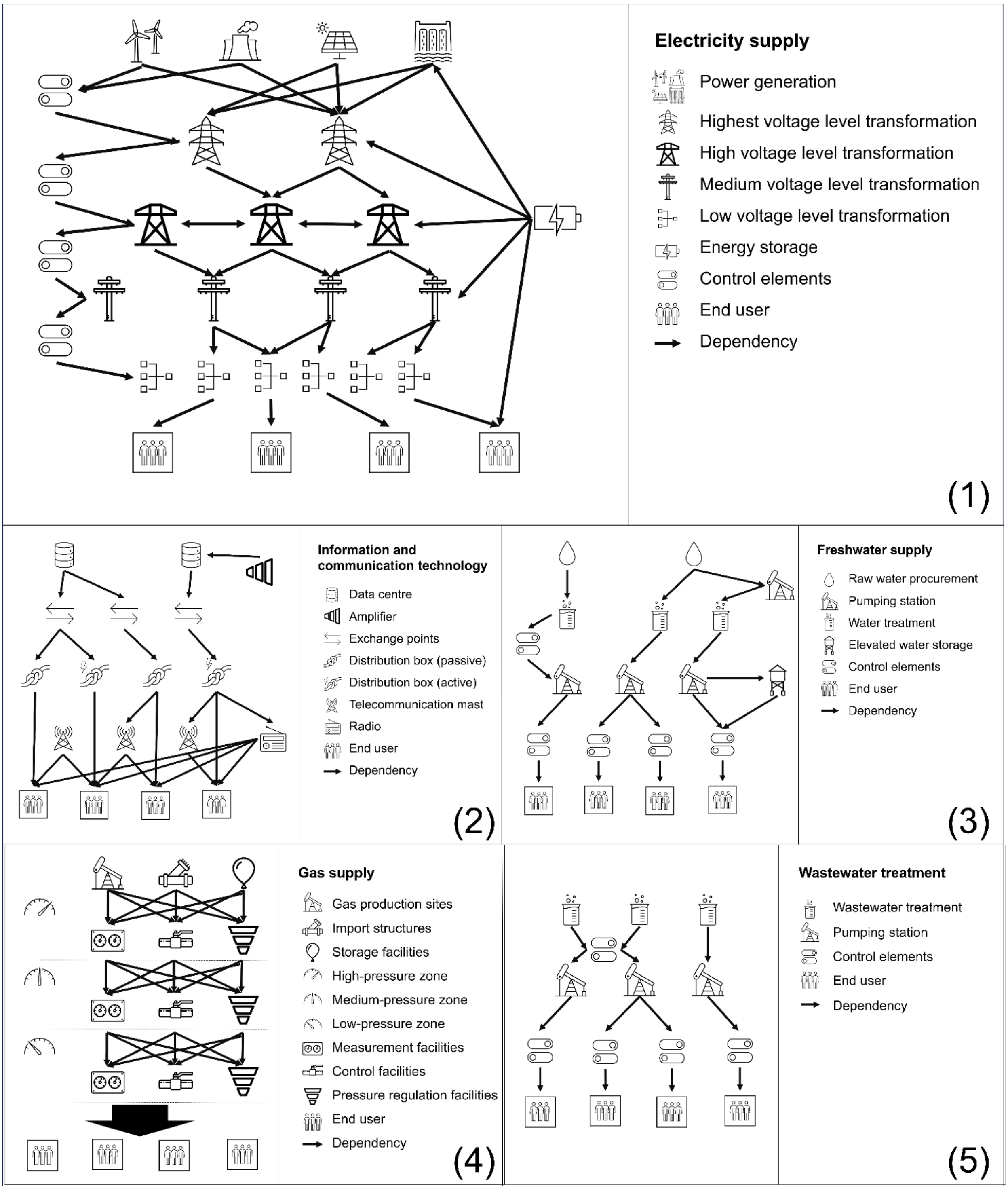


Figure 4-2: Hierarchy of network elements for electricity supply (1), information and communication technology (2), freshwater supply (3), gas supply (4), and wastewater treatment (5).

<u>Prevention and Mitigation</u>: The first measure in this stage, valid for all CI sectors, is to not build in flood-prone areas in the first place and not build linear structures (cables, pipes, roads, etc.) parallel to river bodies. The second generalized measure is to elevate or protect punctual CI assets to prevent impacts from inundation. Both measures can also be assigned to the conventional flood measures. The third generalized measure is

more network-specific and refers to higher redundancy in the CI network by increasing the number of connections to other network islands to better compensate for service disruptions caused by high-level impacts.

Preparation: All CI stakeholders and operators highlighted the importance of inclusion in crisis management committees during the preparation phase. Close collaboration with meteorological services and frequent scanning of flood information systems are also relevant. Another part of the preparedness stage for all CI operators is to organize sufficient NRUs and to make arrangements with service providers required during crisis response and recovery (security firms, technical contractors for repair services, administrators of permits for maintenance vehicles, etc.). A more technical measure that overarches all operators is to organize the availability and operability of mobile flood defence systems and sandbags. For sandbags, it is important to store sufficient bags and sand and organize suitable placement on the CI operator properties. Raising awareness of prevention and mitigation measures at the individual and household levels of CI employees is another measure that increases the availability of these employees during extreme events.

4.2.3 Hierarchical Structures, Flood Impacts, and Exemplary Measures of Critical Infrastructure Sectors

The following sub-chapter includes a brief explanation of the hierarchical structure of the CI sectors considered (cf. Figure 4-2) as well as a description of the impact dynamics that occur during a flood. Subsequently, one example of a measure is given that is specific to the CI sector. The complete extent of the measures per sector can be taken from Appendix 1. Due to the limited extent of this manuscript, the results for the gas sector will not be further discussed but are still present in Figure 4-2 and Appendix 1.

4.2.3.1 Electricity Sector

The electricity supply network consists of several levels of electricity distribution or voltage levels which are connected through transformation stations, also called substations, transformer stations, or on the lowest level street cabinets (cf. Figure 4-2, (1)). Between the voltage levels are the control elements that manage the electricity streams and ensure functionality. These can be operations centred on the highest voltage levels down to remote shutdown devices for the low-voltage level. Energy storage and power generation can be connected at all voltage levels but will not be considered in detail in this study. The specialty of the electricity network is that, from the lowest level, an electrical current, and thus also a dependency, can be directed to the upper transformation levels. Other modelling approaches differentiate the electricity network with a higher granularity, e.g. Asaridis and Molinari (2023).

Impact: Electricity components and water are incompatible because of the high conductivity of water. The presence of water can compromise electrical insulation and increase the risk of electrical accidents at all levels of transformation and control elements.

In addition to the general measures already listed, electricity suppliers must release the threatened transformer stations from the network as a response measure. On the one hand, this prevents health risks through electric shocks; on the other hand, fault currents in installations cannot be passed on to other networks in parallel routing.

4.2.3.2 Information and Communication Technology Sector

The hierarchical system of the ICT sector is understood in the context of this study as follows (cf. Figure 4-2, (2)). ICT services can be divided into mobile network services and cable- or fibre-based Internet and telephone services. Radio stations are also regarded as an important aspect of the ICT sector. The highest punctual assets are the data centres connected to each other through glass fibre connections and amplifiers that maintain signal strength. Cable and fibre networks connect data centres to exchange points, and exchange points with distribution boxes. Distribution boxes can be classified as active (electrically charged) and passive (not electrically charged). From the distribution boxes, telecommunication masts or antennas are supplied; these provide mobile networks to end users. At the same time, distribution boxes also supply end users with cable- or fiber-based internet and telephones.

Impact: Most components mentioned in the ICT sector hierarchy rely on electricity and are thus easily impacted by inundation or disruption in the electricity sector. Only for passive distribution boxes is the impact more related to debris as a side effect of inundation. In addition, telecommunication towers can be affected because they usually need a connection to the wired system and are also active-running currents.

For recovery efforts, active distribution boxes must be repaired using spare parts, which takes a day if sufficient staff and materials are available. Cleaning is sufficient for passive distribution boxes.

4.2.3.3 Freshwater Supply Sector

Freshwater supply sector assets are arranged in three layers. The first layer is raw water procurement, which can be well facilities, surface water intakes, or desalination plants.

The second layer is the water treatment level, usually represented by water works. Under specific conditions, the first and second layers may need to be connected via pumping stations. The third layer represents the water distribution to end users via pumping stations and control elements. In some surroundings, elevated water storage connects end users (cf. Figure 4-2, (3)).

Impact: Flooding affects all layers of the freshwater supply system. For the water procurement well, facilities near water bodies (shore filtrate facilities) are damaged for an indefinite period by the contamination of floodwaters. Water treatment facilities are impacted not only by the water, but also by the entry of pollutants and contaminants that the treatment plant cannot remove. Damaged or disrupted pumping stations cause a pressure drop in the supply lines, cutting the supply for end users. A pressure drop also leads to the entry of foreign substances from outside into the pipeline system.

One potential measure to prevent disruption in the freshwater supply sector is to detach all assets from dependency on the ICT sector. All assets can be operable using mobile networks, but this should be optional. Staff expertise and technical design should ensure that the supply system can be operated without ICT functionality.

4.2.3.4 Wastewater Treatment

The structure of the wastewater treatment system consists of three layers, with the water treatment facility at the top level. Wastewater treatment facilities rely on the functionality of a multitude of pumps that transport sewage water from households to end users (cf. Figure 4-2, (5)). Between these levels, control elements are placed that connect the levels of treatment facilities, pumping stations, and end users.

Owing to the proximity of water treatment facilities to water bodies, backwater quickly enters the treatment facilities where electrical components are damaged, and the different stages of the treatment are biologically or physically damaged. Pumping stations that transfer wastewater fail as a result of direct impact or power failure. This causes wastewater reservoirs to overfill and float, thereby causing health issues. However, it should be noted that the wastewater volume can decrease by 50% in affected areas. The control elements often depend on the power and ICT supply, and thus can fail indirectly.

One preparedness measure specific to the wastewater sector is the closing of backflow preventers, which of course also requires previous installation at the prevention stage as well as the opening of the backflow preventers as a response immediately after the flooding.

4.3 Risk-based Evaluation of Flood Measures for Critical Infrastructures

The presented chapter shows a flood risk management (FRM) process that con-siders critical infrastructure networks (CIN) to evaluate flood measures specific to CI. Two manuscripts deliver the basis for the risk-based evaluations of previously identified flood measures. One manuscript outlines the integration of CIN in FRM (Schotten & Bachmann, 2023a), and the second manuscript defines the modelling approach of CIN for flood risk analysis (Schotten & Bachmann, 2023b).

4.3.1 Consideration of Flood Measures in Flood Risk Management

Flood risk management is grounded in a comprehensive flood risk analysis (FRA) as visualized in Figure 4-3. This analysis consists of identifying flood-prone areas and combining probabilities for recurrence intervals or failure probabilities with the potential consequences of flooding. The FRA uses these values to determine the flood risk for the current situation. The decision to accept or reject the current flood risk necessitates identifying appropriate types of measures along the DRR management cycle (cf. Figure 4-1). As described in the previous chapter, these measures were identified in this manuscript through a participatory approach. The FRA describing the current situation is then also used to test the effectiveness of various flood measures.

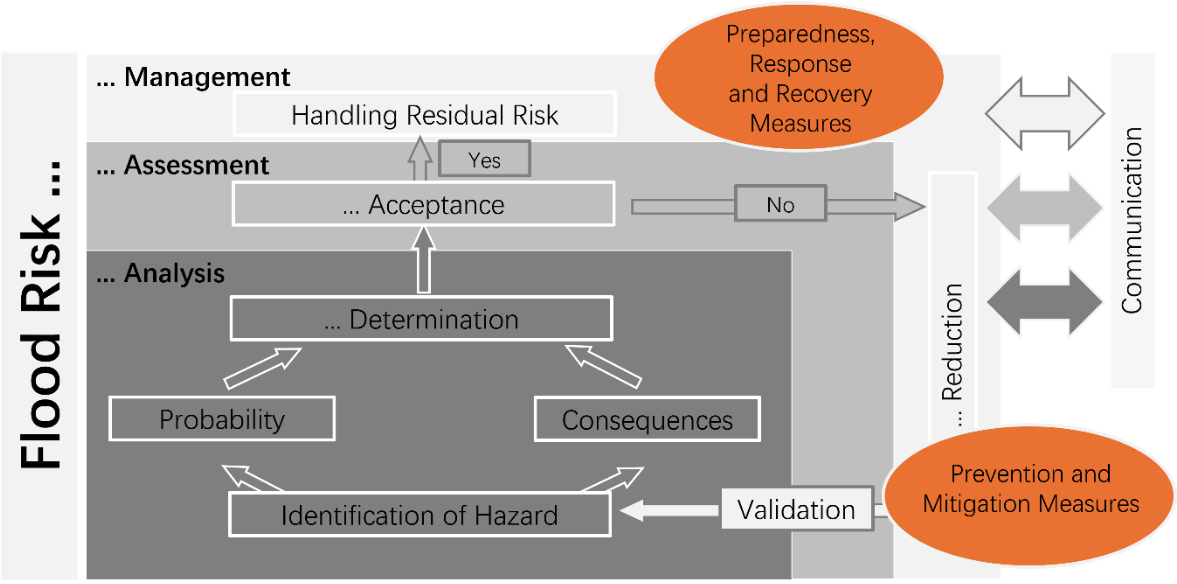


Figure 4-3: Flood measures placement in the process of flood risk management (Schotten & Bachmann, 2023a).

4.3.2 Model-based Evaluation of Flood Measures for Critical Infrastructures

The comparison of the effectiveness of flood measures requires quantification of the flood risk, which is especially challenging with a focus on critical infrastructure services. In the presented case study, a topology-based network modelling approach that has been defined elaborately previously by (Schotten & Bachmann, 2023a) is used to analyse the consequences of flooding on multisectoral CIN. The CIN modelling approach is connected to the PROMAIDES framework, which combines hydraulic and consequence modelling capabilities, as well as probability, to derive flood risk at a catchment-based level (Bachmann, 2012).

The modelling approach utilizes three types of network elements to represent CI networks: point elements, polygon elements, and connector elements. Point elements represent CI structures using attributes and are assigned to sectors and levels within their sector. The threshold attribute of the point element determines the water depth, which causes complete failure of the point element, and the recovery time attribute defines the time a point element is disrupted after threshold values are crossed. The connector elements link the point and polygon elements. Moreover, the connector elements transmit disruptions to the interconnected elements. Polygon elements establish the spatial scope of their connections with point elements, either entirely or partially. Furthermore, the polygon definition is based on the number of end users or consumers it serves with a particular service.

The three types of elements and their attributes allow the modification of the CIN model in its current state to represent a range of measures. For example, accelerated response measures can be represented by a decreased recovery time of point elements. Mobile flood protection walls and elevation of critical components can be represented in the model by increasing the threshold value. Additional redundancies or emergency structures can be represented by newly added point and connector elements. Therefore, the chosen modelling approach enables the quantification of a wide range of measures previously identified in Appendix 1.

The quantifiable output of the modelling approach delivers $P_{dis,sec}$ [people], the area and number of disrupted people per element *i* and sector *sec*. The recovery time of the centre element indicates the time of disruption t_i [d] for the other network elements. The multiplication of $P_{dis,sec}$ and t_{sec} for all end-user elements per sector *e* results in the population time per sector T_{Pop} [people · d]; see also (Murdock et al., 2018):

$$T_{Pop,sec} = \sum_{i=0}^{e} P_{dis,sec,i} \cdot t_i \tag{4-1}$$

T_{pop} is used in combination with the hydrological probability p_{hyd} per return period scenario k to derive the risk as a decision-making unit. The sum of all products of T_{Pop} and p_{hyd} per return period scenario k results in the risk of consequences for CI R_{CI} [people·d/a]:

$$R_{CI} = \sum_{k=0}^{n} T_{Pop,sec,k} \cdot p_{hyd,k} \tag{4-2}$$

After determining the flood risk for the current state, measures can be introduced into the CIN model, as previously described. The flood risk for the current state can then be compared with the flood risk under consideration of measures to determine the potential benefit of measures and deliver a basis for more objective decision-making for the implementation of measures (Schotten & Bachmann, 2023b).

4.4 Case Study – Potential of Flood Measures in the Vicht Catchment

In this chapter, a proof-of-concept is introduced for the application of the catalogue for CI flood measures in combination with a flood risk management model workflow. The

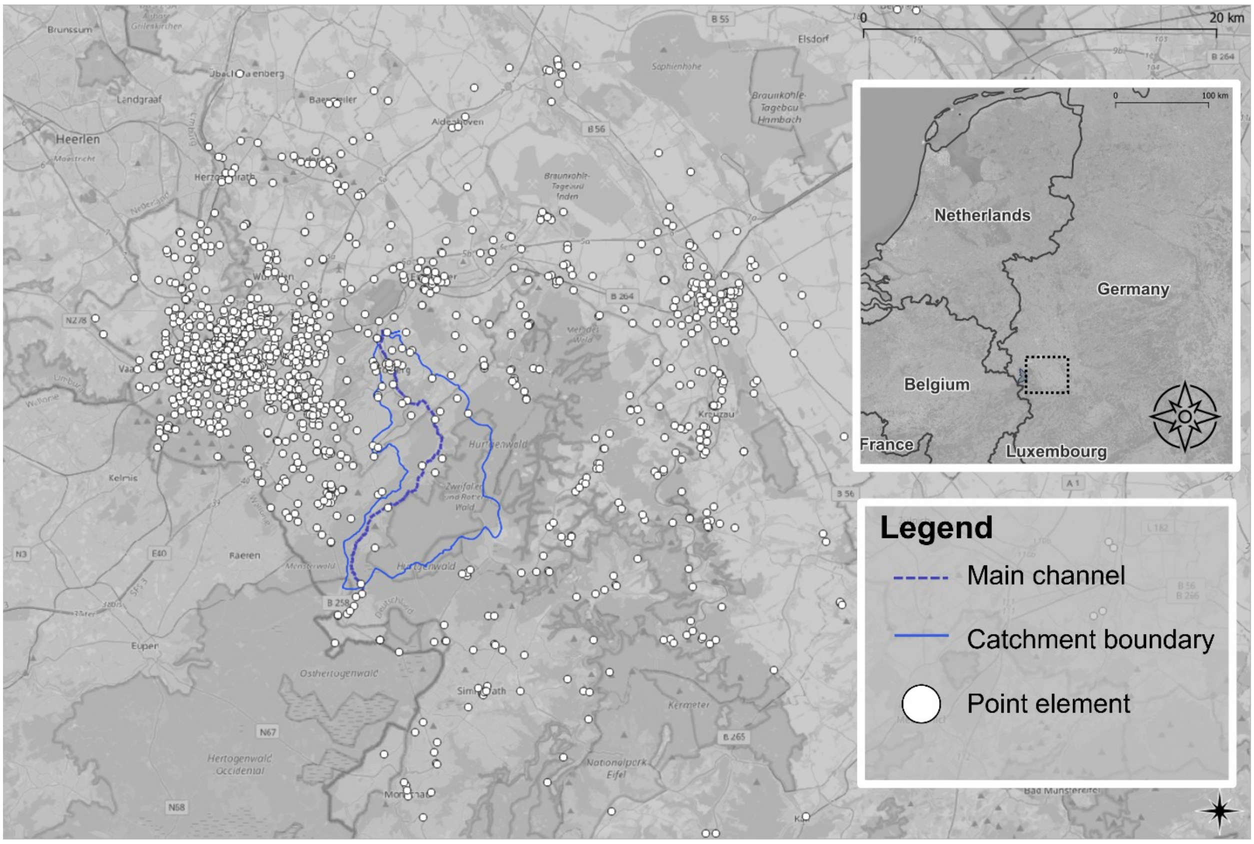
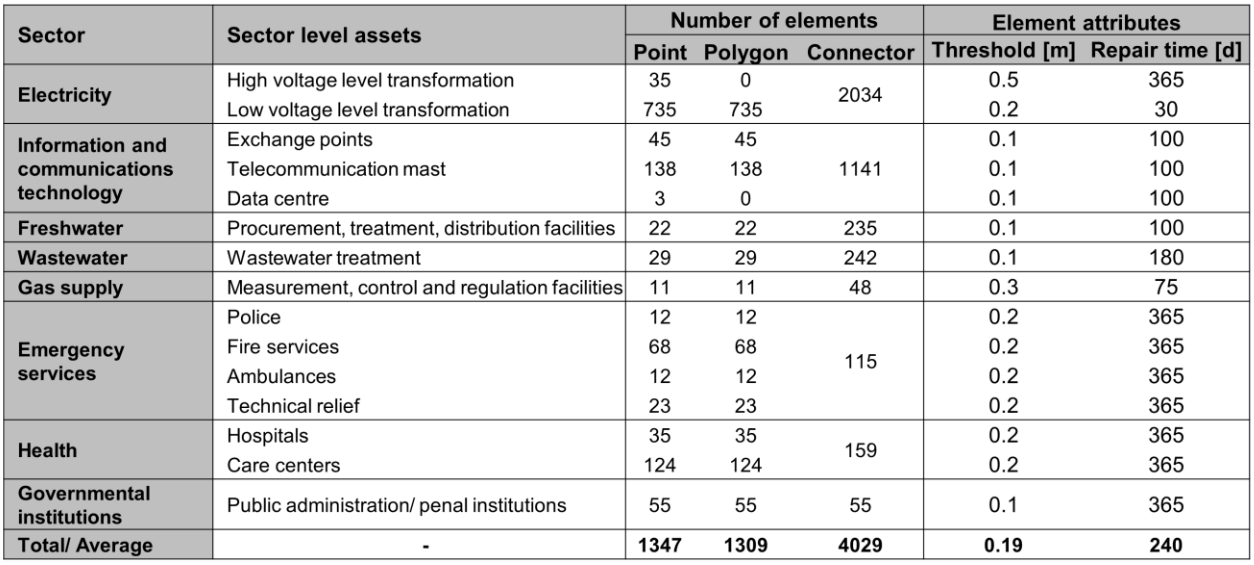


Figure 4-4: Catchment boundary for the area of investigation at the western border of Germany, next to Belgium and the Netherlands. The point elements represent CI assets that are represented in the critical infrastructure network model.

Table 4-2: Represented sectors and sector-level assets, number of CI network elements and associated model attributes.



Sector	Sector level assets	Number of elements			Element attributes	
		Point	Polygon	Connector	Threshold [m]	Repair time [d]
Electricity	High voltage level transformation	35	0	2034	0.5	365
	Low voltage level transformation	735	735		0.2	30
Information and communications technology	Exchange points	45	45	1141	0.1	100
	Telecommunication mast	138	138		0.1	100
	Data centre	3	0		0.1	100
Freshwater	Procurement, treatment, distribution facilities	22	22	235	0.1	100
Wastewater	Wastewater treatment	29	29	242	0.1	180
Gas supply	Measurement, control and regulation facilities	11	11	48	0.3	75
Emergency services	Police	12	12	115	0.2	365
	Fire services	68	68		0.2	365
	Ambulances	12	12		0.2	365
	Technical relief	23	23		0.2	365
Health	Hospitals	35	35	159	0.2	365
	Care centers	124	124		0.2	365
Governmental institutions	Public administration/ penal institutions	55	55	55	0.1	365
Total/ Average	-	**1347**	**1309**	**4029**	**0.19**	**240**

focus of the study encompasses the catchment area of Vichtbach or Vicht, which covers a region of approximately 68 km² and features a medium-sized mountain stream with a length of 23 km (cf. Figure 4-4). The Vicht springs close to the Belgium border, and the main channel passes through five localities before flowing through the town centre of Stolberg and finally mouthing into the Inde River.

The case study area was chosen along a river body that had significant impacts during flooding events in Western Europe in 2021. Comparable studies used the flooding in 2021 as a benchmark for what-if analyses, such as (Bruijn et al., 2023). At the same time, the catchment offers a testing ground of a relatively small size and is thus comprehendible. The combination of recent flooding and good news coverage, in combination with a small catchment area, allows for good checks of plausibility. Additionally, a quality check of the availability of OSM data coverage showed good results (OpenStreetMap contributors, 2017). The electricity and telecommunications sectors were represented by a sufficient number and type of point elements to form a hierarchical system.

This chapter consists of the introduction of the network model, its elements, and their associated attributes, as well as a hydraulic model including hydrological probabilities. Consecutively, the network model and hydraulic model are used to test potential measures. The free software PROMAIDES is used for hydraulic modelling, CI consequence modelling, and derivation of the risk, as introduced in Section 4.3 (Bachmann, 2023).

4.4.1 Critical Infrastructure Network Model

The network model for this proof-of-concept overarches the catchment area by at least 30 km to ensure that cascading effects are not cut by the boundary of the hydrological catchment boundary (cf. Figure 4-4). Only structures within Germany are considered because sectors and sector-level assets in the catchment are assumed to not have major cross-country dependencies. All point elements shown in Figure 4-4 are derived from the OSM database (OpenStreetMap contributors, 2017). The point elements, as well as the polygon and connector elements, are differentiated for every sector-level asset, as shown in Table 4-2. Point specific attributes such as threshold and repair time were derived for point elements from a range of sources (Koks et al., 2022; Poirier et al., 2022). Fresh water, wastewater, and gas supply are not represented in the model as a hierarchical system, as introduced in Section 4.2, because the data density was not sufficient. The polygon elements are derived using the closest distance method (Voronoi polygons) for every point element necessary (Koks et al., 2022; Poirier et al., 2022). In combination with population density data, a number of end users are associated with each polygon element (Meta - Data for Good, 2023). The connector elements are visualized in

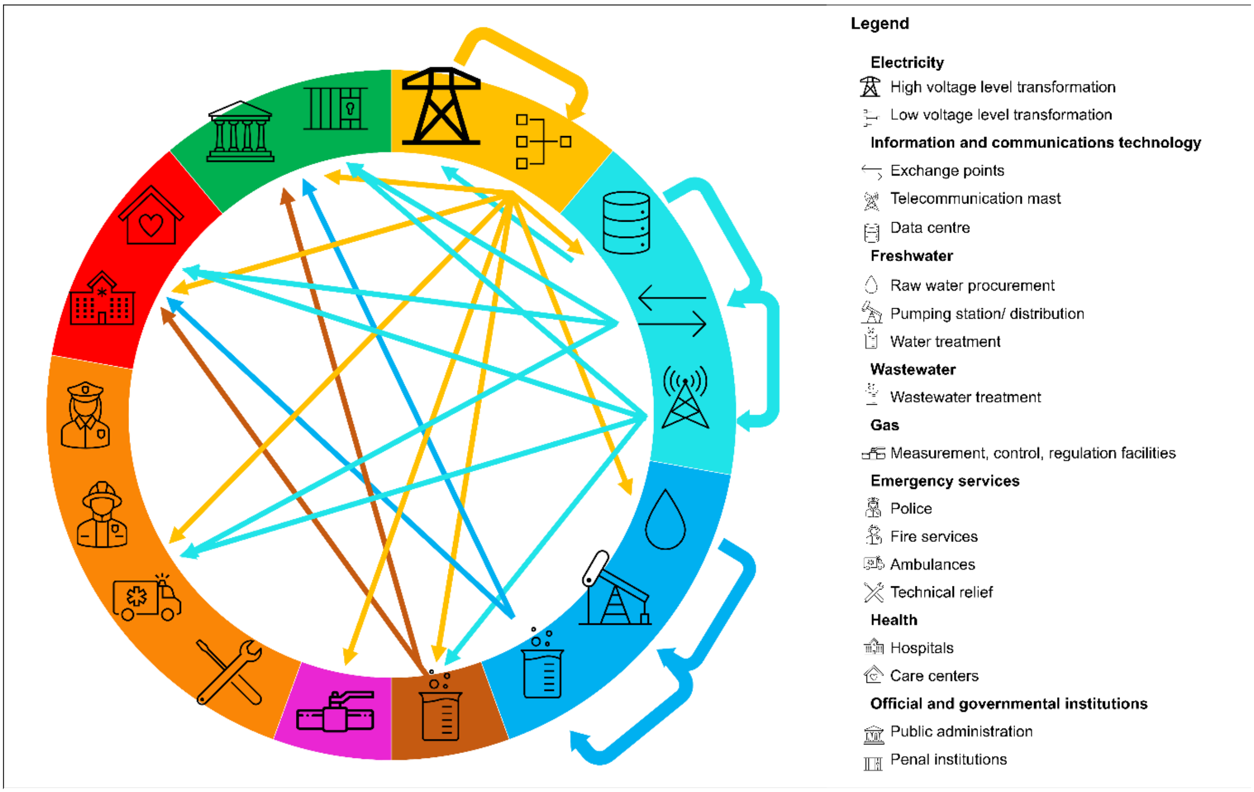


Figure 4-5: Connector elements showing which point element types have dependencies on each other in the Vicht case study. Transsectoral connector elements are represented by arrows inside the circle and sectoral connector elements are represented by arrows outside of the circle.

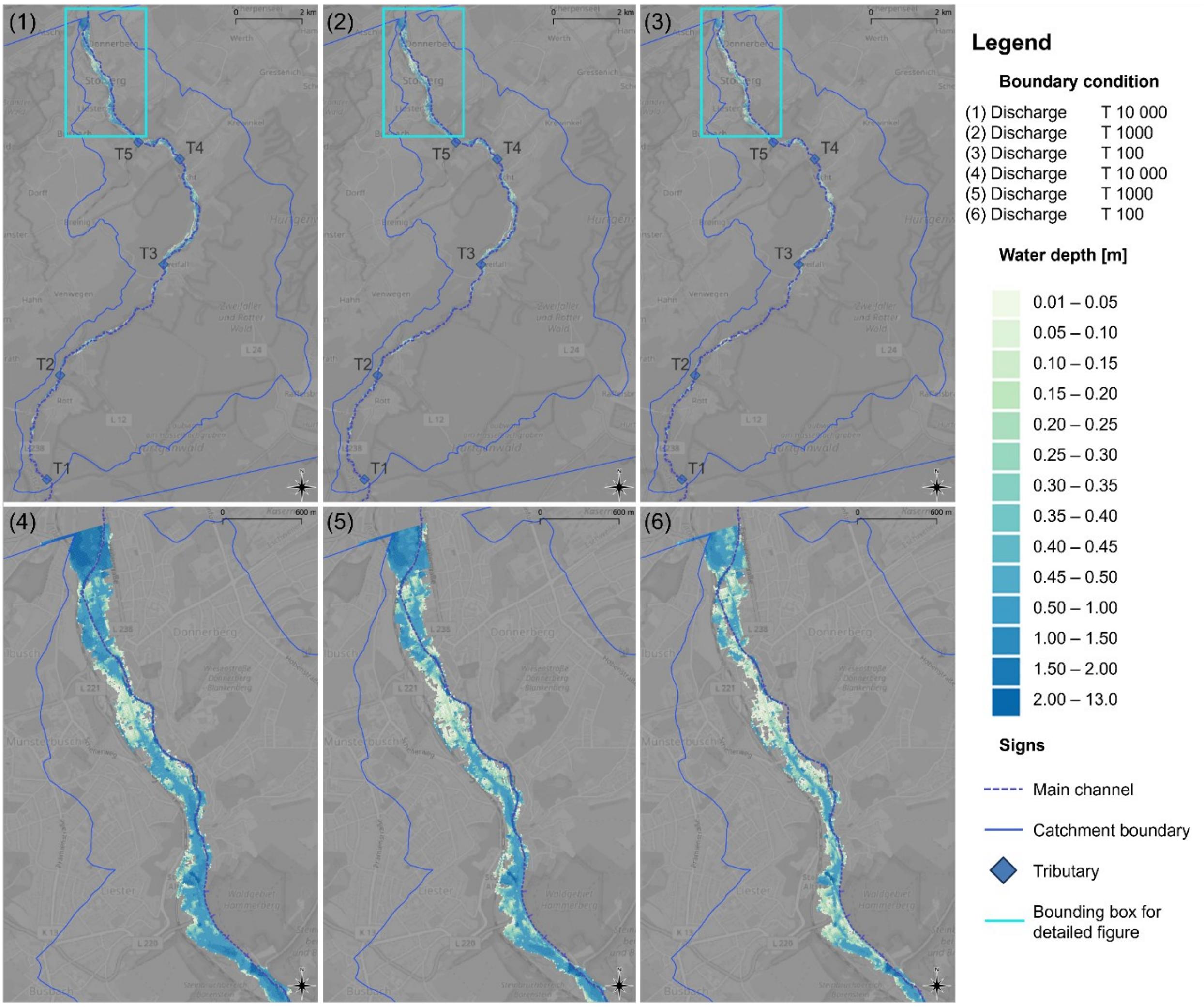


Figure 4-6: Water depth from the Vicht derived from the hydraulic model for three return periods; (1)-(3) shows the result for the entire catchment; (4)-(6) show the result for the detailed view of the city centre of Stolberg. T1-T5 describe the tributaries entering the main channel.

Figure 4-5 showing the dependencies of every point element per sector and level in that sector as identified during the interviews in Section 4.2. The dependencies are derived from a common infrastructure grid operated in Germany. Dependencies from the electricity, ICT, and wastewater sectors apply to all elements of the secondary CI sectors (emergency services, health, and official and governmental institutions).

4.4.2 Hydraulic Model: Input and output

Another component for the flood risk analysis is the hydraulic model, which consists of a 1D part for the Vicht main channel and 2D rasters covering the entire catchment. The purpose of the hydraulic model is to derive inundations and velocity 2D information and superpose them with the CI network. The results of the hydraulic model additionally allow the assessment of the time course of a flood event. As an input for the hydraulic model, a digital elevation model with 10 m resolution is used. The 1D river model con-

Table 4-3: Boundary condition discharge for the hydraulic model per tributary.

Return period T	Unit	T100	T1000	T10 000
Probability of occurence p_{hyd}	**[1/a]**	**1.45%**	**0.495%**	**0.055%**
Tributary 1	[m³/s]	67.66	97.05	125.72
Tributary 2	[m³/s]	18.20	26.10	33.82
Tributary 3	[m³/s]	43.49	62.38	80.81
Tributary 4	[m³/s]	16.14	23.16	30.00
Tributary 5	[m³/s]	14.50	20.79	26.94

sists of 99 profiles with a width of 50 m and a distance of ~230 m in between profiles. For the hydraulic boundary a synthetic discharge was used as a T100 event, and based on a logarithmic distribution, T1000 and T10 000 discharges are derived (cf. Figure 4-6 and Table 4-3). No measurements were used to derive the hydraulic boundary since the differentiation from fluvial and pluvial effects of historic events was not possible. Therefore, the hydraulic boundary as well as the return periods are not the most reliable, because a long set of measurements is necessary to derive reliable return periods. However, the purpose of this proof-of-concept is not to derive the most accurate values for return periods but to show the risk-based approach of CI analysis and measure planning by calculating water depths associated with different probabilities of occurrences (cf. Table 4-3). Therefore, a wide range of return periods is essential. The hydraulic model uses discharges as boundary conditions, which were added to the main channel of the Vicht in five tributary inflows (cf. (1) - (3), Figure 4-6). A detailed view of the city of Stolberg shows the inundated areas in (4) - (6) of Figure 4-6. The values of the discharge boundary conditions for each tributary are listed in Table 4-3.

4.4.3 Current Risk

The combination of the hydraulic model and the CI network model delivers an analysis of the current flood risk situation for the area of interest. Figure 4-7 shows the directly disrupted CI point elements in the catchment area for a T10 000 flood event and indi-

Table 4-4: Impacted CI point elements for each return period and failure type.

Return period	Failure type (Electricity/ ICT/ Freshwater/ Other)			
	Direct	Sectoral	Transsectoral	Total
T100	3 (0/ 0/ 0/ 3)	0 (0/ 0/ 0/ 0)	0 (0/ 0/ 0/ 0)	3 (0/ 0/ 0/ 3)
T1000	6 (1/ 1/ 0/ 4)	9 (6/ 3/ 0/ 0)	21 (0/ 2/ 1/ 18)	36 (7/ 6/ 1/ 22)
T10 000	7 (1/ 1/ 0/ 4)	9 (6/ 3/ 0/ 0)	21 (0/ 2/ 1/ 18)	37 (0/ 2/ 1/ 18)

rect sectoral and indirect transsectoral failures outside the catchment area. The results for a T10 000 yearly flood event help identify a worst-case scenario. Table 4-4 shows the total number of impacted CI point elements and each failure type for every return period. Another output is the yearly risk of people disrupted from critical infrastructure services per year $R_{CI,\,pop}$ as well as the population time disruption from the CI services R_{CI}. Table 4-7 shows $R_{CI,\,pop}$ and R_{CI} for each sector in the current state. For comprehension, the sectors of emergency services, hospitals, and care centres have been cumulated to health, and governmental institutions and penal facilities to social. The method for deriving the $\mathrm{R_{CI}}$ has been introduced previously (cf. Section 4.3). The most severely affected sector according to $R_{CI,\,pop}$, and R_{CI} is the health sector, which is also a result of the bundling of specific sector services (four different emergency services, hospitals, and care centres).

In addition to the quantitative results of the model, spatial extents of CI disruptions are highlighted as shown in Figure 8, where the CI service disruptions for the electricity, ICT, and freshwater sectors are shown through the CI polygon elements. A T1000 event is chosen for Figure 4-8 as the medium intensity scenario of the three available ones,

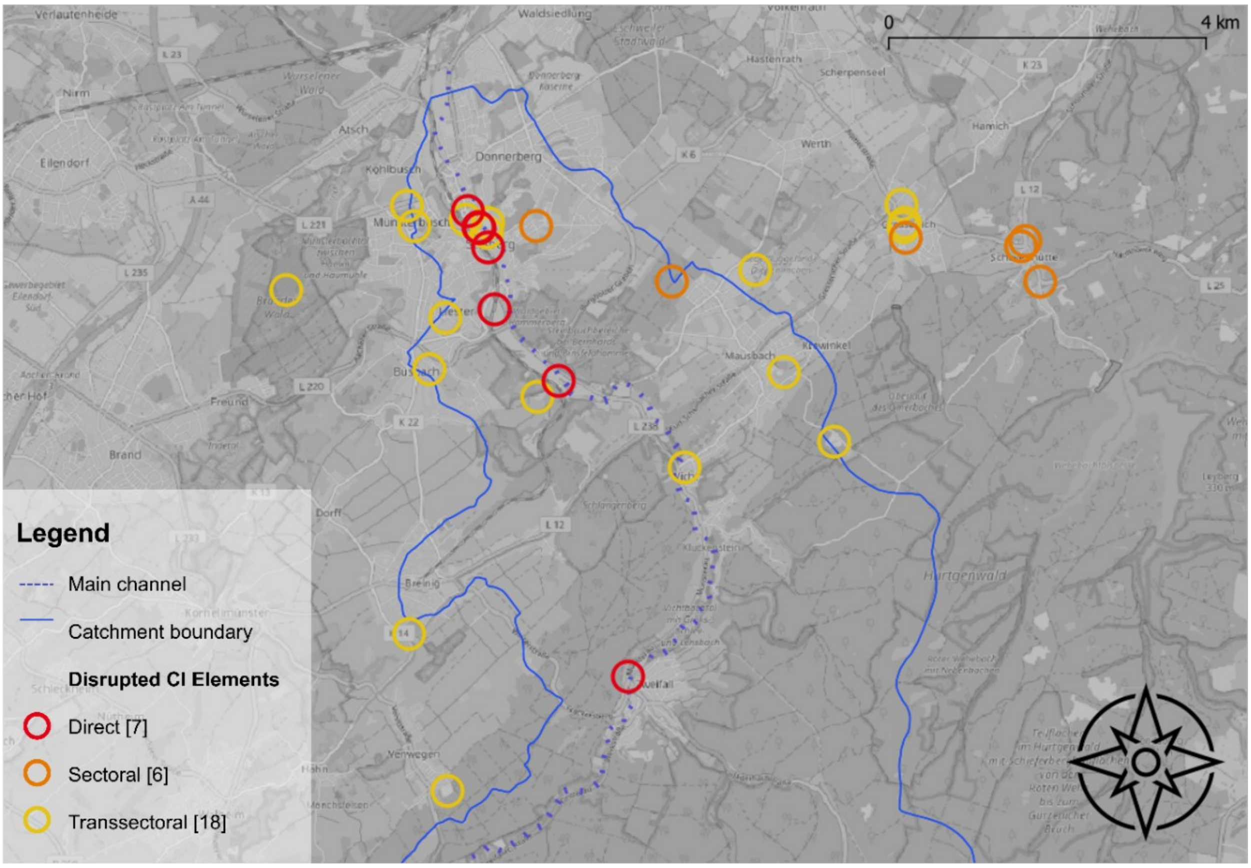


Figure 4-7: Disrupted critical infrastructure elements based on a T10 000 flood event in the Vicht catchment.

although and as indicated previously the discharges are not empirical. The model results show that in parts of the city centre of Stolberg, all three mentioned sectors are disrupted simultaneously. The ICT polygons are shown double layered because they refer to wireless and cable-based internet.

Owing to the limited availability of integrated datasets for validation, only anecdotal validation for the model results is executed. Posts in a Stolberg-focused social media group were analysed during the flooding in July 2021 (Facebook, 2024). The hydraulic boundary does not fit to the flooding in 2021 but can give an impression of the sectors that are involved. Posts that commented on a disrupted CI service and a specific location are shown in Figure 4-8 as validation points. Most posts were concentrated in the three CI sectors previously mentioned. The comparison with the model results confirms the accuracy of the modelling results in seven of 13 validation points. However, the validation can only confirm that a disruption occurred, and not the duration of the disruption.

4.4.4 Testing Measures for Effectiveness

In this part of the case study, the flood measure catalogue was utilised to identify potential measures. The network model in combination with the hydraulic model provides evidence about the potential benefits of the measures. Flood measures are necessary to

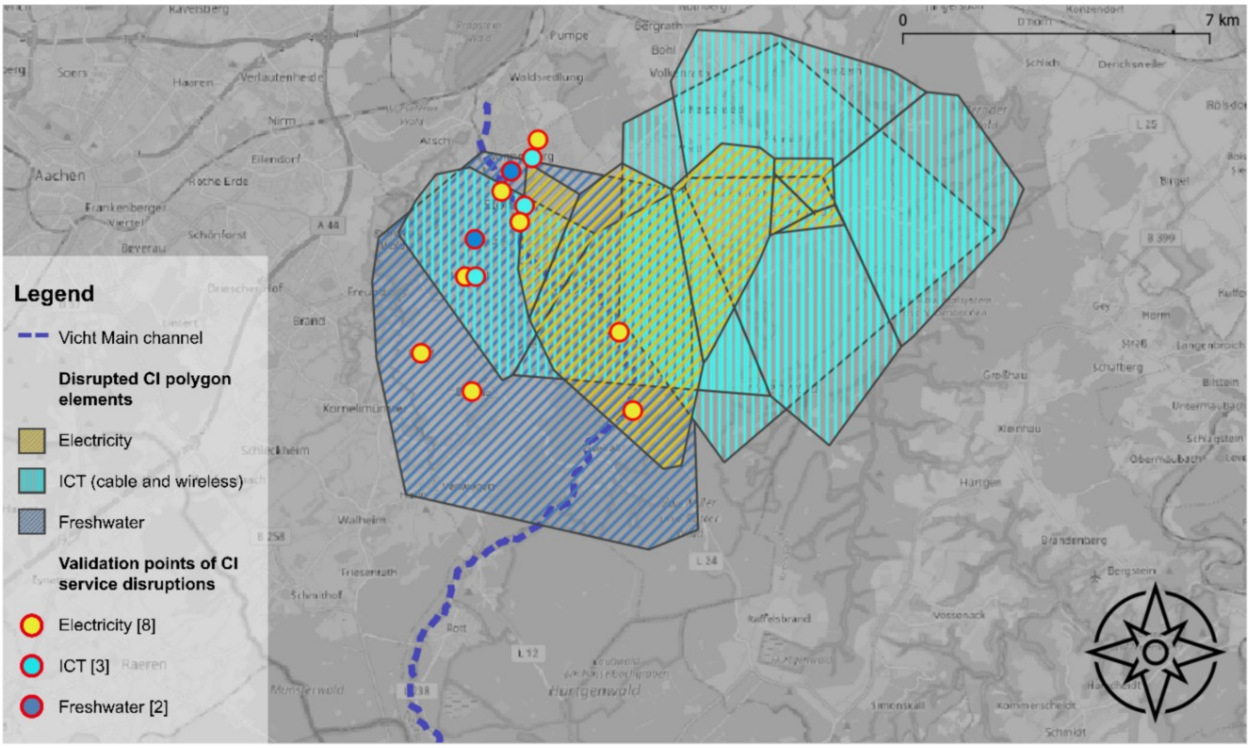


Figure 4-8: CI polygon elements disrupted through T1000 flood event for the electricity, ICT, and freshwater sectors. Points indicate locations and sectors where a disruption was indicated in social media posts.

improve the current situation and to make a shift from mere flood risk analysis towards flood risk management (cf. Section 4.3). Some of the measures collected can be tested in the CIN model environment (cf. Section 4.4.4) and compared to each other for decision makers to choose the most suitable solutions. Appendix 1 is used to determine the measures that could be considered for the case study. In addition to the table, the Cascade Potential Value (CPV) is used to highlight which CI point elements have high potential for measures to be effective. The *CPV* of each point element determines the number of dependent CI point elements (Schotten & Bachmann, 2023a). A high CPV indicates that the failure of a point disperses further and causes indirect sectoral or trans-sectoral disruptions. A high *CPV* and a direct disruption highlight the necessity to check for measures. Figure 4-9 shows a spatial overview of these points, as well as the locations chosen for five potential measures (Measure I. – V.) from three different sectors. Table 4-6 describes the measures that have been considered and links each measure to the cell from which they originate in Appendix 1.

Measure I considers a shorter recovery time of the electricity substation owing to the storage of spare transformers. Measure II applies to the same substation but prevents disruptions by raising the disruption threshold value by elevating the active components and installing watertight cable entries. Measure III refers to an ICT exchange point that is additionally connected to an electricity source in another catchment. It is well noted that flooding within the neighbouring catchment is not analysed, and thus Measure III inherits an additional unknown risk. Measure IV concerns a directly disrupted telecommunication mast, which is elevated. Measure V involves the acquisition of network replacement units that have the potential to decrease the disruption time as long as operating resources, such as fuel, are available, which is usually 48 h. Measure I and V both cause the reduction of recovery time but with different mechanisms. Whereas Measure I is effective due to the fast replacement of damaged components in a

Table 4-6: Measures considered in the benefit analysis of the CIN model framework.

Number	Sector	Disrupted point element	Measure description	Model implementation	Reference to cells in Table 2
I.	Electricity	Substation	Storing of spare parts such as transformers for shorter duration of repair work	Decreased recovery time = 30 d	A5/ F5
II.	Electricity	Substation	Elevation of substation including pressurized water-tight cable entries	Increased threshold = 1 m	A4/ F4
III.	ICT	Exchange point	Redundant power supply from unaffected area	Redundant power supply from low transformation area in unaffected area	B4/ F4
IV.	ICT	Telecommunication mast	Water-proof cable inlets and elevated	Increased threshold = 0.5 m	B4/ F4
V.	Freshwater	Freshwater treatment facility	Network replacement unit to decrease disruption time from power cut (fuel storage 48 h)	Decreased recovery time = X – 2 d	C2/ F2

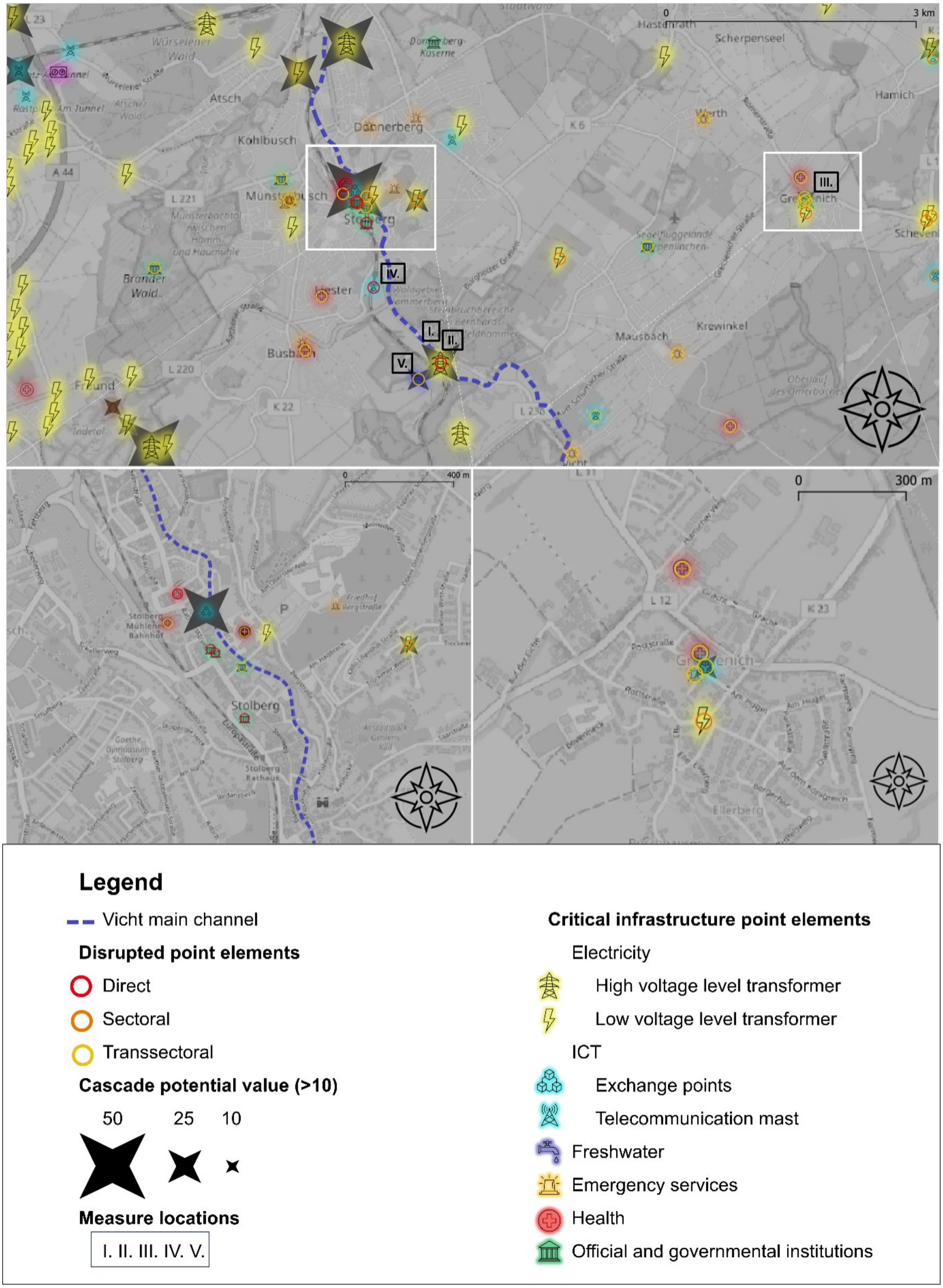


Figure 4-9: View of a section of the catchment area of the Vicht, including the CI point elements, cascade potential values, disruptions, and locations of considered measures.

Table 4-7: Risk of population disruption and risk of population time of disruption from CI services per year through flooding in the Vicht catchment for the current situation and with consideration of flood measures for CI.

Measure/Scenario	Electricity	Difference	ICT	Difference	Freshwater	Difference	Health	Difference	Social	Difference	Total	Difference
	Risk - Disrupted Population R_{CI} [people·days/a]											
Current situation	37 099	-	81 404	-	83 897	-	570 418	-	110 429	-	883 248	-
Measure I.	3 049	34 050	14 113	67 292	6 896	77 001	289 602	280 816	42 043	68 386	355 703	527 545
Measure II.	0	37 099	8 086	73 318	0	83 897	264 455	305 963	35 919	74 510	308 460	574 787
Measure III.	37 099	0	29 694	51 711	83 897	0	566 244	4 174	110 429	0	827 363	55 885
Measure IV.	37 099	0	73 318	8 087	83 897	0	570 418	0	110 429	0	875 161	8 087
Measure V.	37 099	0	81 404	0	83 438	459	570 418	0	110 429	0	882 789	459
	Risk - Disrupted Population Time $R_{CI,\,Pop}$ [people/a]											
Current situation	102	-	282	-	230	-	1 563	-	303	-	2 479	-
Measure I.	102	0	282	0	230	0	1 563	0	303	0	2 479	0
Measure II.	0	102	81	201	0	230	725	838	98	204	904	1 575
Measure III.	102	0	140	142	230	0	1 551	11	303	0	2 325	153
Measure IV.	102	0	201	81	230	0	1 563	0	303	0	2 398	81
Measure V.	102	0	282	0	230	0	1 563	0	303	0	2 479	0

network element, Measure II uses a temporary measure to replace a broken network element temporarily.

The inclusion of the scenarios in the modelling framework results in numbers for the risk of disrupted people $R_{CI,Pop}$ and the risk for population time disruption R_{CI}. $R_{CI,Pop}$ is a simplified version of R_{CI} that focuses solely on the cumulative risk to the number of people affected, without considering their associated disruption time. Table 4-7 summarizes the risk for each sector or cluster and shows the effective difference in the current situation caused by the specific measures. The results show that Measure I and II are most effective to decrease the risk. Though, the remaining Measures III, IV and V can also help to reduce the sector specific risk.

4.5 Discussion and Outlook

The present study is separated into two parts. In part one, a literature study and interviews with CI stakeholders and experts are used to derive a catalogue of potential flood measures. In part two, a case study showcases how measures are included in a network model. Both parts are discussed, and an outlook is provided in the following section. The measures collected were not quantified during the interview with regard to the potential of increasing the threshold of resistance to flood water depth or recovery time. The interview partners indicated that this remains a highly specific attribute. It is recommended that a systematic collection of measures, including quantification of their attributes, be continued to reduce this uncertainty. Additionally, it is recommended to represent the temporal progression of the setup and dismantling of measures in the CIN modelling approach in more detail, for example, in a system response function as done by (Mathavanayakam et al., 2022; Murdock et al., 2018). The basis for such temporal progression could be reports written by CI operators or public administration on previous flood events, such as the flood chronic from the drainage and wastewater treatment enterprise of Dresden, Germany (Böhm, 2003).

During interviews it was frequently mentioned that the acquisition of funding for flood measures remains a challenge. Following the principle that 'there is no glory in prevention', there is no reward for a more robust and resilient CI service. It has even been stated for some CI sectors in Germany that investments in disaster resilience cannot be passed on to consumer prices. However, ensuring the stability of CI services also during extreme events has been shown to be extremely important due to cascading effects and costs (World Bank & Asia Pacific Economic Cooperation, 2021). Therefore, the World Bank asks for the risk and potential cost to be understood before disasters occur (Calcutt & Ranger, 2020). The present study shows how to quantify the effectiveness of flood measures for CI and provides a basis for the acquisition of funding that supports policy- and decision-makers in the CI domain.

Very few studies combine a hierarchical system for more than two CI sectors (Emanuelsson et al., 2014; Pant et al., 2018). In this case study, the representation of the freshwater, wastewater, and gas sectors was not possible in a hierarchical system due to data availability. Therefore, it is recommended to collect and provide CIN data from multiple sectors. Additionally, it is recommended to extend the presented case study by comparing the potential costs of the suggested measures and improve the linkage to funding the implementation stage and support the decision making. Another addition worth considering for future case studies is testing the quantifiable risk-reduction that is achievable by combining measures in the model. An overlap of areas of impact could result in lower effectiveness than the sum of individual measures might suggest. Conversely, particularly broad measures could be identified that, despite being combined in the model representation, approach the sum of their individual results.

Nevertheless, the case study introduces a range of uncertainties and assumptions that should be clearly communicated to decision-makers to ensure they understand the quality of the results when implementing measures. These assumptions and uncertainties have an influence on the model output which need to be communicated to the recipients of the model outcome (Schotten et al., 2024). As a part of a disclaimer of model outputs, it is recommended to execute sensitivity analyses to assess the model quality. Although these inaccuracies exist, the method still provides a strong foundation for stakeholders to make informed decisions about which measures could impact these complex systems.

For the investigated area, only publicly available data and information were used. Validation of the network model and hierarchical system for each CI sector was not possible without the participation of CI operators. The results of the flood risk network analysis were verified anecdotally by checking social media posts during that time. This verified the disruption of electricity and ICT supply in three specific locations, and showed that disruption in the freshwater supply could not be shown in the results but was mentioned in social media posts. When deriving general statements from this study, it must be considered that this proof-of-concept is applied to a relatively small catchment area and that only fluvial flooding is considered. For more general discussions, it is recommended to consider other spatial extents and types of natural hazards.

The flood measure catalogue can be divided into two types of measures. Firstly, flood risk reducing measures that prevent harmful consequences, and secondly, resilience-enhancing measures that focus on capacity and adaptive capabilities. The presented case study showed that the recovery time can be included in a modelling approach and be quantified in the flood risk for population disruption time (cf. Equation 4-2). Therefore, measures initially regarded as resilience-enhancing are included in the risk concept. Nevertheless, the modelling approach does not have the capability to incorporate all resilience-enhancing measures (cf. Appendix 1) that have been identified, which outlines the limitation of the presented method. More data which describes attributes such as recovery time or threshold values are needed and can help extend what is to be considered in a model-based flood risk management approach.

4.6 Conclusion

It is concluded that a flood measure catalogue for critical infrastructures can be applied in network model-driven flood risk analysis.

A literature study and interviews with CI experts were conducted and assembled into a CI flood measure catalogue. The catalogue is structured for five CI sectors and offers a generalized category. This structure was further differentiated for each stage of the DRR cycle. Thus, the catalogue can be used to further develop CI network case studies for the implementation stage by suggesting practical measures to the scientific community. At the same time, the catalogue helps to verify the applicability of CI network analysis methods: the more measures that can be included, the more applicable an analysis method may be. However, a range of measures remains either unquantifiable or, at the very least, presents significant challenges in quantification, particularly concerning organizational measures.

The measure catalogue is used to extend a state-of-the-science flood risk analysis for CIN by considering potential flood measures, thus paving the way from flood risk analysis to flood risk management for CI. The presented case study of a small catchment in the west of Germany provides a proof-of-concept for the application of the measure catalogue. The CIN Module from the PROMAIDES framework is used to combine the CI network modelling, hydrological probabilities, and spatial and quantitative hydraulic model results. It is shown that flood risk as a concept can be used to derive a solid metric to describe flood consequences in the CI domain including the consideration of probabilities. A network modelling approach was used to check the effectiveness of some CI measures, while at the same time the limitations of the chosen network modelling method have been explored in the discussion. Effective measures could be checked, and a significant reduction in the affected population could be proven for the catchment area, and the overall resilience of the CI network could increase.

This method ultimately provides policymakers and stakeholders in the CI domain with a quantified, risk-based foundation for making informed decisions on sector specific measures to enhance infrastructure resilience in each step of the DRR management cycle.

5 DATA FOR CRITICAL INFRASTRUCTURE NETWORK MODELLING OF NATURAL HAZARD IMPACTS: NEEDS AND INFLUENCE ON MODEL CHARACTERISTICS

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Resilient Cities and Structures 2024, 3(1)

DOI: 10.1016/j.rcns.2024.01.002

Natural hazards impact interdependent infrastructure networks that keep modern society functional. While a variety of modelling approaches are available to represent critical infrastructure networks (CINs) on different scales and analyse the impacts of natural hazards, a recurring challenge for all modelling approaches is the availability and accessibility of sufficiently high-quality input and validation data. The resulting data gaps often require modellers to assume specific technical parameters, functional relationships, and system behaviours. In other cases, expert knowledge from one sector is extrapolated to other sectoral structures or even crosssectorally applied to fill data gaps. The uncertainties introduced by these assumptions and extrapolations and their influence on the quality of modelling outcomes are often poorly understood and difficult to capture, thereby eroding the reliability of these models to guide resilience enhancements. Additionally, ways of overcoming the data availability challenges in CIN modelling, with respect to each modelling purpose, remain an open question. To address these challenges, a generic modelling workflow is derived from existing modelling approaches to examine model definition and validations, as *well as the six CIN modelling stages, including mapping of infrastructure assets, quantification of dependencies, assessment of natural hazard impacts, response & recovery, quantification of CI services, and adaptation measures. The data requirements of each stage were systematically defined, and the literature on potential sources was reviewed to enhance data collection and raise awareness of potential pitfalls. The application of the derived workflow funnels into a framework to assess data availability challenges. This is shown through three case studies, taking into account their different modelling purposes: hazard hotspot assessments, hazard risk management, and sectoral adaptation. Based on the three model purpose types provided, a framework is suggested to explore the implications of data scarcity for certain data types, as well as their reasons and consequences for CIN model reliability. Finally, a discussion on overcoming the challenges of data scarcity is presented.*

5.1 Introduction

Critical infrastructures (CIs) are responsible for the supply of essential services and goods. They are organised in sectors which have intra- and inter-sectoral dependencies. Owing to such dependencies within (intra-sectoral) and across (intersectoral) components of different critical infrastructure (CI) sectors, critical infrastructure networks (CINs) are formed. Disruptions in one sector can lead to impacts in other sectors and cause chain effects (Korkali et al., 2017; Rinaldi, 2004). The role of CIs in society's safety and security is receiving increasing acknowledgement due to an increasing number of threats such as extreme natural events, military conflicts, global pandemics, and cyberattacks, and the demand to increase their resilience is ever growing.

The purposes that CIs serve are versatile, and societies' reliance on them is not easily conceived due to the complex arrangements and dependencies between CI sectors. This especially applies to densely populated urban environments which sustain themselves owing to an equally dense CIN. One way to capture CIs' supply of essential services and goods is by utilising models. Invariably, representing the multifaceted purposes of CIs results in similarly multifaceted modelling approaches, on which comprehensive overviews can be found in the literature (Ouyang, 2014; Rinaldi, 2004; Sun et al., 2022). Such CIN models may analyse direct disruptions caused, for instance, by natural hazards as well as indirect disruptions caused by cascading effects transmitted through dependencies (Thacker et al., 2017). In addition to the analysis of disruptions, CIN models are used to develop measures and quantify their effectiveness for every step of the disaster risk reduction cycle (Ani et al., 2019; Schotten & Bachmann, 2023b; United Nations, 2015), which ultimately plays a key role in improving the resilience of cities with regard to previously introduced threats.

Invariably, CIN modelling approaches rely on a range of data and information inputs. Data acquisition for modelling inputs poses a challenge, which was also identified by the United Nations (UNDRR, 2021). The challenge of gathering input data may limit the potential utility of CIN modelling approaches in contributing to the evaluation and management of resilience in urban environments for coping with natural hazards. There are several reasons for the lack of availability or accessibility of these data, such as the data protection of CI users, data confidentiality of CI operators, sensitivity of CI and their essential services during conflicts, and unawareness of the benefits and data needs of CIN models. Despite the challenges in data and information availability and accessibility, CIN modelling approaches are becoming a popular tool for capturing larger-scale interdependent infrastructures, disruption, and cascading effects. Lack of data and information is often complemented by assumptions in all stages and data types of the modelling process, which may affect the quality of the output and thus the reliability of the decision made based on the CIN model outputs. The first component of a solution is to bridge the gap between missing data and information. Categorisation of the data types needed for CIN models is the fundamental step required for filling the gap. Johansson & Månsson (2020) and Ramachandran et al. (2016) outlined the need for data and methods to support empirical and predictive assessments of CI resilience. However, currently, very few systematic reviews are available on the types of data needed. Second, a discussion of the implications of data availability and accessibility on model characteristics is needed. Model characteristics are further defined as the capabilities, attributes, and reliability of CIN modelling approaches and their output. Discussions on the impact of data scarcity on models in general are given by Huang & Bardossy (2020). Very few discussions have focused on how these assumptions are made to overcome data scarcity and how they affect the quality and aptness of CIN model characteristics to make actual judgements. These exchanges may lead to more thorough data acquisition practices, enable dialog with potential data providers, and lead to a better assessment of CIN model results.

The presented work provides a categorisation and explanation of data input types for a more systematic way of thinking about data needs and assumption implications. For each data input type, a definition is given, as well as literature references to existing datasets if available or approaches in need of this data type. The categorisation is based on individual stages within a generalised CIN modelling workflow. The presented work is delimited in two important dimensions: the purpose that CIN models fulfil is to define the specific needs for data. For example, the vulnerability of CIN to cyber-attacks and the identification of maintenance needs of infrastructure require different information and data. In the present work, the scope is limited to only considering extreme natural events as impacts to CIN to explore the intricacies involved, but the defined methodology is generally applicable. The various techniques to derive the features of natural hazards, such as numerical modelling, data-driven, or empirical methods, are not outlined in this work because the focus is on the impact of extreme natural events on the exposed CIN. Another limitation is the explicit focus on CIN modelling approaches conventionally termed "network-based approaches" (Ouyang, 2014) or "graph-based modelling approaches" for gathering data needs. The represented modelling approaches are further referred to as CIN modelling approaches. These approaches have subcategories, such as flow-based network models, which treat the flow of commodities through the CIN as the driving characteristic. Another sub-category which is also included in this work are topology-based network modelling approaches, which concentrate on the functionality of CI assets based on topological attributes of the network as defining characteristics. Other sub-categories for CIN modelling approaches, such as agent-based or system-dynamics-based approaches, must be mentioned in this context but are not considered explicitly further on because of their more specific data needs. In the introduction chapter, the background and motivation of this work were outlined, and a short review of the literature was presented. The main purpose of this paper is to provide an overview of data needs for CIN modelling and a framework to assess potential repercussions of data scarcity. Therefore, a generalised modelling workflow and its stages were derived. Based on every stage, the required input data types are categorised, and the literature is presented for each data type possible. Subsequently, a framework is suggested to assess the implications of data scarcity on the CIN models. Three case studies are introduced with a focus on one missing input dataset per category, the assumptions necessary owing to the missing data, and the resulting effects on the model characteristics. The present work then discusses how to overcome data scarcity and concludes the paper (cf. Sections 5.4 and 5.5).

5.2 Critical Infrastructure Network Modelling Stages & Data

5.2.1 A Generalised Critical Infrastructure Network Modelling Process in Stages

As previously mentioned, a wide range of data needs may be encountered in different CIN modelling approaches. To capture these in a systematic manner, a broadly formulated and generic multi-stage modelling process is derived, inspired by work stages frequently encountered in previous studies on CIN network modelling (Ani et al., 2019; Ouyang, 2014; Rinaldi, 2004). Each stage forms a category which is examined separately for their data needs (cf. Section 5.2.2). It is noted that this categorisation is not exhaustive but serves as a starting point for the development of CIN modelling studies. Figure 5-1 shows these stages, as well as one overarching stance. The *definition of the model purpose* drives every single stage at the beginning of the modelling assignment. It is not necessarily driven by data, but drives the data need. The stage of *validation, calibration, and plausibility evaluation* overarches the entire process because it can be applied to all modelling stages as well. Thus, validation and model purpose have a distinctive role in the graphical representation of Figure 5-1 at the beginning and end. Additionally, Figure 5-1 shows these stages as individual components which are included and considered depending on the modeller's preferences. Some modelling workflows only consider certain predefined stages.

By definition, models are simplified representations of nature or systems. Thus, the first stage of modelling is outlining the model purpose, which is defined by the intention that applies to CIN modelling efforts. Rather than requiring much data per se, the purpose of each study focuses on the choice of modelling approach and, consequently, data requirements. The purpose frames expectations on the usability and types of results which the model should eventually provide (for instance, decision support for strategic planning, information for disaster management, creation of knowledge, awareness building) and specifies users and target groups (such as academic researchers, utility providers, regulators, etc.). Overall, the model purpose is to determine other model characteristics, such as system boundaries, potential output, and the target group. An in-depth discussion of the relationship between model purpose, data needs, data availability, and model characteristics is given in Section 5.3.

The next stage is defined as the *mapping of infrastructure assets*. The intention of this stage is to set up a network representation of the CI under study, considering their topological characteristics. This includes the transformation of information on physical infrastructure components into network modelling elements, such as nodes and links or vertices and edges. Nodes represent individual entities, and links represent the dependencies between those entities.

Consecutive to asset mapping is the *quantification of dependencies*. In this stage, dependencies within the CIN (intra-sectoral) and between different infrastructure networks (inter-sectoral) are identified, quantified, and included as explicit network model elements.

The next step is the *quantification of CI services* for the assembled network. The objective of this stage is to obtain a quantifiable extent of the service levels provided by the CIs under study, including information on the service area, recipients of the services, and demand patterns for these services.

In the stage of *impacts of natural hazards*, the exposure of infrastructure assets to natural hazards and their consequences are considered. Knowledge is needed on the area and type of natural hazards causing structural damage or disruptions of CI functionality, as well as on the impact-functionality relationships linking infrastructure damage to their ability to provide their services.

The subsequent stage involves the *appraisal of adaptation measures*. The target of this stage is to evaluate the effect of measures (designed for adaptation, mitigation, or other purposes) implemented at any potential level of the system under study (i.e. infrastructure network components, dependencies, network structure, etc.) on a specified target metric.

The steps of the disaster risk reduction cycle are approximated in the following stage *determination of response and recovery*. The objective of this stage is to analyse the post-disruption behaviour of the modelled system and its trajectory until it reaches a certain performance state (such as pre-disaster service levels or a new status quo). Not considering the response and recovery leads to an inaccurate representation of disruptions and, ultimately, an incomplete representation of CINs under the impact of extreme natural events.

The final stage is the *validation, calibration, and plausibility evaluation* of previous individual stages and refers to the examination of the system behaviour with sufficient accuracy. This stage can consist of calibrating the input parameters, checking for plausibility, or verifying the input and output data (Aumann, 2007; McCarl, 1984). Several model validation approaches exist (Farina et al., 2013; Sargent, 2011) that entail different data requirements. Usually, this is performed by comparing the field or experimental data to the model outputs, referring to the same (or a sufficiently similar) scenario. Finally, it must be noted that model validation should also be conducted according to the model purpose, rather than aiming to achieve a perfect representation of the studied systems.

5.2.2 Data Needs Derived from Critical Infrastructure Network Modelling Process Stages

Grounded in the stages of the generalised modelling process defined in Section 2.1, an in-depth literature review was conducted to collect frequently occurring data needs, types, and, if available, potential data sources. These data types are introduced for every modelling stage, as shown in Figure 5-1. Every icon indicates a type of data and information that can be relevant for CIN modelling.

5.2.2.1 Mapping of Infrastructure Assets

Spatially explicit modelling studies start out with a need for geospatial information on CI component locations as point elements and occasionally as polygons describing infrastructure extent. Depending on the spatial scale and geographical region of interest, the availability of such information is highly varied; infrastructure location data may be readily accessible, curated, and openly provided through official (e.g. governmental) sources, as by the *Homeland Infrastructure Foundation-Level Open Data* of the U.S. Department of Homeland Security (United States Department of Homeland Security, 2021) or the *Geoportal* of the Swiss Federal Administration (Coordinating body for federal geoinformation, 2023). The only way to obtain infrastructure data in less affluent regions is to rely on crowd-sourced mapping platforms such as OpenStreetMap, which often have unknown quality and completeness ratings (OpenStreetMap contributors, 2017). Besides regional differences in data availability, certain infrastructure sectors are notorious for data scarcity: road infrastructure, for instance, is relatively well mapped and available (Barrington-Leigh & Millard-Ball, 2017) because the availability of its location is a prerequisite for its usage. Many subterranean components tend to have mapping gaps, which impede large-scale risk analysis, as is common in the water sector (Stip et al., 2019). Further data scarcity concerns arise from resolution issues, that is, when detailed sub-components of infrastructure networks are required for analyses, as opposed to a more simplistic reliance on high-level components. For instance, when representing the power grid through different types of power plants, substations, transformers, high- and medium-voltage transmission lines, power towers, low-voltage distribution lines, and poles instead of simply mapping the most important transmission lines and plants. In the case of missing data sources, workarounds are applied depending on the model purpose. In case a model is generated to develop and test a modelling framework, for example, the generation of synthetic infrastructure data has been used among others in (Ellingwood et al., 2016; Guidotti et al., 2016), machine-learning-based inference of infrastructure data for the global power transmission grid (Arderne et al., 2020), or even omission from the scope of study (Stip et al., 2019).

5.2.2.2 Quantification of Dependencies

Since the seminal work of (Rinaldi, 2004) on the importance of dependencies among critical infrastructures, many frameworks for categorising dependencies have been developed (Ouyang, 2014; Sun et al., 2022). However, data are needed to identify dependencies in the first place and enable the consideration of potential chain reactions. Empirical approaches have focused on a range of methods such as expert judgement and media coverage (de Bruijn et al., 2019; Zorn et al., 2021), yet to date, no comprehensive dependency databases exist which thoroughly document these (cf. (Luiijf & Klaver, 2021) for a European-wide effort to build one). The level of detail for such identification efforts is often limited by the resolution at which utility providers share data (Dueñas-Osorio & Kwasinski, 2012). Deductions of dependencies often remain at a sectoral scale (Luiijf et al., 2009; Zimmerman, 2004), which does not link appropriately to the resolution of many CIN modelling approaches. Furthermore, quantification of hence-identified dependencies is often summarised under terms such as ‘coupling behaviour’ (Rinaldi, 2004) or ‘coupling strength’. Ideally, dependencies should incorporate the notion of input quantities at the supporting side which relate to output quantities at the dependent side, and of the degree to which certain impacts on a dependency source propagate down to a dependency target. Quantification efforts have proven to be data-intensive, relying on time-dependent disruption and restoration data (Dueñas-Osorio & Kwasinski, 2012; Zorn & Shamseldin, 2016). While such coupling behaviours are sometimes implicitly quantified through (lack of) redundancy in the network topology or through failure tolerance threshold attributes, deterministic and binary dependency formulations still prevail owing to a lack of refined data to capture more elaborate dependency relationships.

5.2.2.3 Quantification of CI Services

Per definition, CIs provide essential services to a number of end-users, including the population, businesses, and other infrastructure. The performance provided by infrastructure can be expressed not only in terms of services but also in terms of goods. However, in the present work, only services are mentioned. As CIN modelling is usually concerned with impact estimation, a multitude of data regarding CI services are necessary. First, knowledge about the characteristics of the population, including their number, socioeconomic status, and vulnerabilities, served from a particular infrastructure asset is required. Moreover, data on the characteristics of businesses and other infrastructure assets served could also be required. In the absence of detailed data, a number of substitute techniques are commonly employed, such as the estimation of a service area using geometric methods such as Voronoi decompositions or shortest-path algorithms (Evans et al., 2018; Mühlhofer, Koks, et al., 2023; Pala et al., 2014; Pant et al., 2018). Voronoi polygons can also be used for dependency quantification, as in (Ani et al., 2019). Other options include the use of surveys (Dong et al., 2020) or aggregated customer and census data (Zorn et al., 2020). Additionally, service demand pattern data may be required for both asset functionality determination and impact estimation (Guidotti et al., 2016), especially when examining the societal impacts of disruptions (Stock et al., 2023). Although sufficiently accurate estimations exist for certain CI services, such as water distribution networks (Blokker et al., 2010; Mazzoni et al., 2023), they may be more difficult to obtain for other CI services, such as emergency services or the financial sector. CI service data, as defined herein, are usually difficult to obtain because of legislative restrictions, economic competition, or general absence. Consequently, most studies in the scientific literature resort to a number of assumptions and inference approaches.

5.2.2.4 Impacts of Natural Hazards

From a CIN modelling perspective, it is important to capture when and how individual infrastructure assets subject to natural hazard impacts and translate this direct asset-level failure to system-level indirect failures. It should be noted that failure does not necessarily imply a binary state, as is commonly used (Poirier et al., 2022), but it can also refer to reduced functionality. Asset damage or failure is a product of complex interactions between the characteristics of the asset and those of the hazard considered (Merz et al., 2010), making failure identification a data-intensive task. In practice, asset damage is usually linked to certain hazard parameters (e.g. via appropriate curves) according to the type of asset examined. These parameters may vary depending on the infrastructure or hazards considered. For example, in the case of flooding, a range of hydrological characteristics can be considered (Hammond et al., 2015), including whether the asset is flooded or not (Ranger et al., 2011), inundation depth (Chen et al., 2016), water velocity (Kreibich et al., 2009), flood duration (Kameshwar et al., 2021), and water chemical composition, although inundation depth is the most commonly used parameter in practice (Jongman et al., 2012). In the case of earthquakes, fragility curves that link element damage to ground motion parameters such as peak ground acceleration (PGA), peak ground velocity, and peak ground displacement (Pitilakis et al., 2014) are commonly employed. Additionally, insights into how damage translates to service or functionality reduction are required. In addition to the identified hazard failure mechanisms, storms and fires must be mentioned. Several functionality mechanisms have been considered in practice, such as binary functionality states (Sun et al., 2020), discrete functionality states (Evans et al., 2020; Vamvakeridou-Lyroudia et al., 2020), or continuous functionality (Pregnolato et al., 2017). These mechanisms are infrastructure- and hazard-specific. A binary state realistically represents the failure of electric power assets under a flood scenario, whereas a transportation network requires a continuous functionality representation. Consequential is the consideration of multi-hazards which may further complicate infrastructure response (Koks et al., 2019). A simple superposition of the previously mentioned response attributes may not suffice for multi-hazard environments because a compound event could either have more severe impacts on the disruption or be the same as a singular event. Thus, disruption functions must be generated individually for each multi-hazard-sector combination. Finally, exposure to natural hazards may not be described deterministically only, but also under consideration of extrinsic uncertainties, for example, meteorologic uncertainties, and intrinsic uncertainties, for example, resulting from a system's inherent variability. Currently, the lack of comprehensive datasets regarding infrastructure failure under a multitude of hazards is a bottleneck in risk and resilience analyses.

5.2.2.5 Determination of Response & Recovery

Modelling the response and recovery process of interdependent CIs naturally relies on most of the aforementioned data to represent the interdependent infrastructure system itself, yet requires various additional data: component repair times (Koks et al., 2022); quantitative relationships between the repair state of components and service provision levels (Murdock et al., 2018) - conceptually the inverse of the damage-functionality relationship mentioned above–; data on response actions including work capacities and repair priorities or the rerouting of CI supply flows (Lee II et al., 2007). This refers to the transformability of infrastructure assets under the stress of natural hazards. Frequently used component repair time tables are partly available through the technical manuals of FEMA's Hazus Program (Federal Emergency Management Agency, 2022) or from ATC-13 data (Federal Emergency Management Agency, 1989) for a wider range of buildings pertaining to different social function classes. Such tables deliver partial insight into the infrastructure components covered and may not always be directly transferable to regions other than the US for which they were designed. Given the complexity of the task, many recovery studies tend to remain at the sectoral level rather than the infrastructure component level and do not incorporate the multitude of uncertainties involved in these processes (Almoghathawi et al., 2019).

5.2.2.6 Appraisal of Adaptation Measures

Commonly, the viability of adaptation measures is evaluated by trading off benefits against costs, which requires data on either side and at various scales of a network. Multi-criteria analyses and, most commonly, cost-benefit analyses, are performed for many types of hazards and individual infrastructure sectors (Davlasheridze et al., 2019; Ryan & Stewart, 2017; Wild et al., 2019). As measures may act on different aspects of the risk chain, such as reducing a component's vulnerability or exposure to a certain hazard, or on the hazard intensity itself, data are needed to parameterise the working mechanism and hence quantify the risk aversion benefit adequately. Evaluating measures with regard to their co-benefits and costs in other CI sectors requires adequate parameterisation of the above-mentioned dependency relationships. The latter is particularly crucial when evaluating the effects of system-level adaptation measures (Murdock et al., 2018). For instance, these measures aim to enhance resilience by modifying dependency relationships instead of fortifying individual components. Examples of system-level adaptation measures are increasing redundancies, reducing failure propagation behaviour, etc.), or modification of end-user demands and response capacities. Drawing on the level of destruction and disruption from real-world extreme events, however, it may be concluded that the performance of adaptation measures is still rarely evaluated at the system level, nor do measures tend to target system-level adaptation (Koks et al., 2022).

5.2.2.7 Validation, Calibration & Plausibility Evaluation

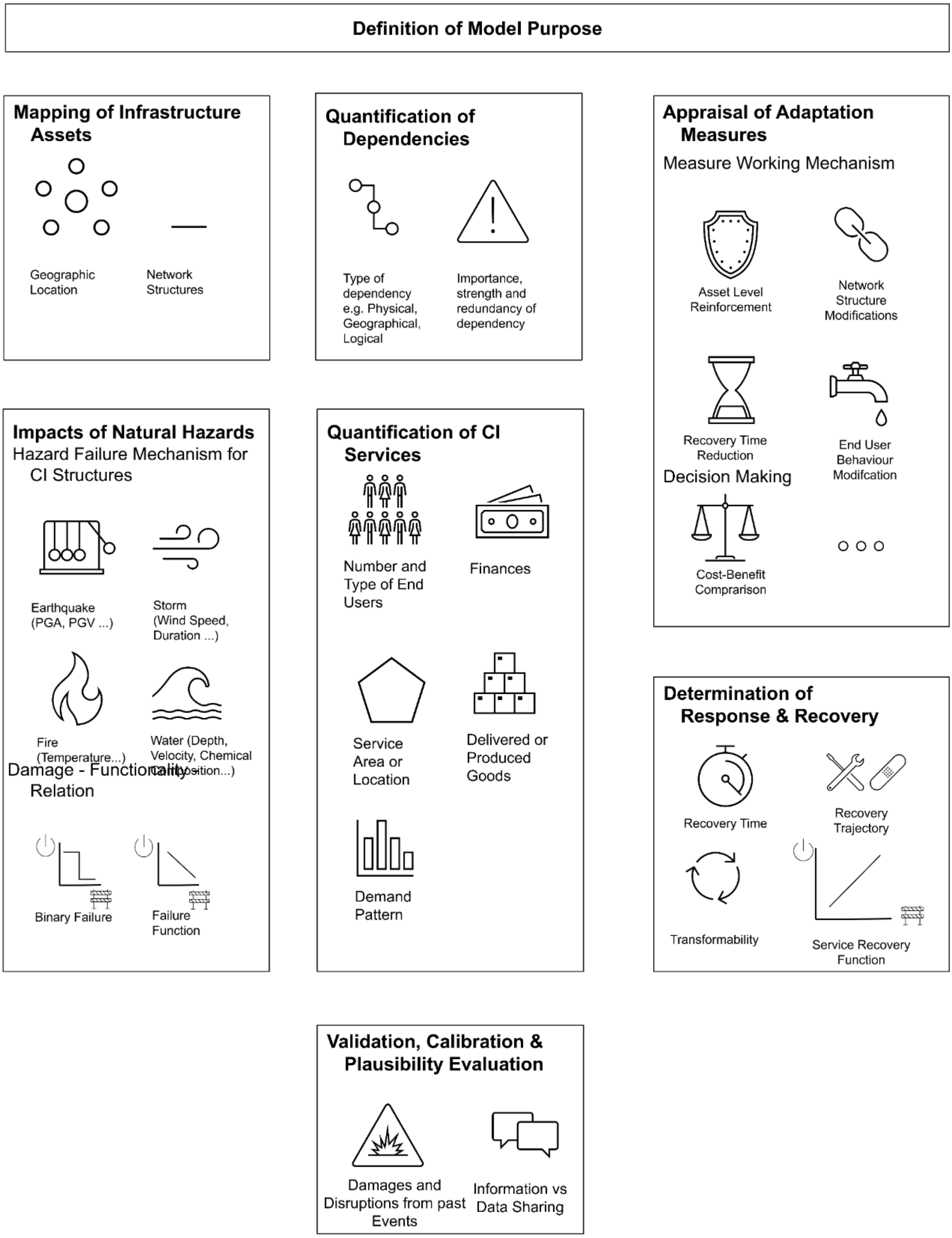


Figure 5-1: Generalised stages of critical infrastructure network modelling workflow for hazard with the boxes including the data types required in those stages.

In the context of modelling CI responses under hazard scenarios, studies have focused on collecting field data from past events. Such data might include print media and social media or infrastructure and disruption damage and disruption reports of past events

(Mühlhofer, Koks, et al., 2023), utility providers' service outage statistics and restoration timelines (Cimellaro et al., 2014; Dueñas-Osorio & Kwasinski, 2012), and reports of response measures taken (Briere et al., 2018). Methodologies that require data collected from expert and stakeholder elicitation processes may also be employed (Voinov & Bousquet, 2010). It is important that these datasets are of sufficient quality in terms of reliability, consistency, completeness, and detail, which in turn requires additional verification. In general, there is a lack of established CI model validation approaches in the scientific literature, and the validation of CI models is rarely comprehensive owing to the unavailability of relevant, homogeneous data.

5.3 Framework to Assess Model Implications due to Data Scarcity

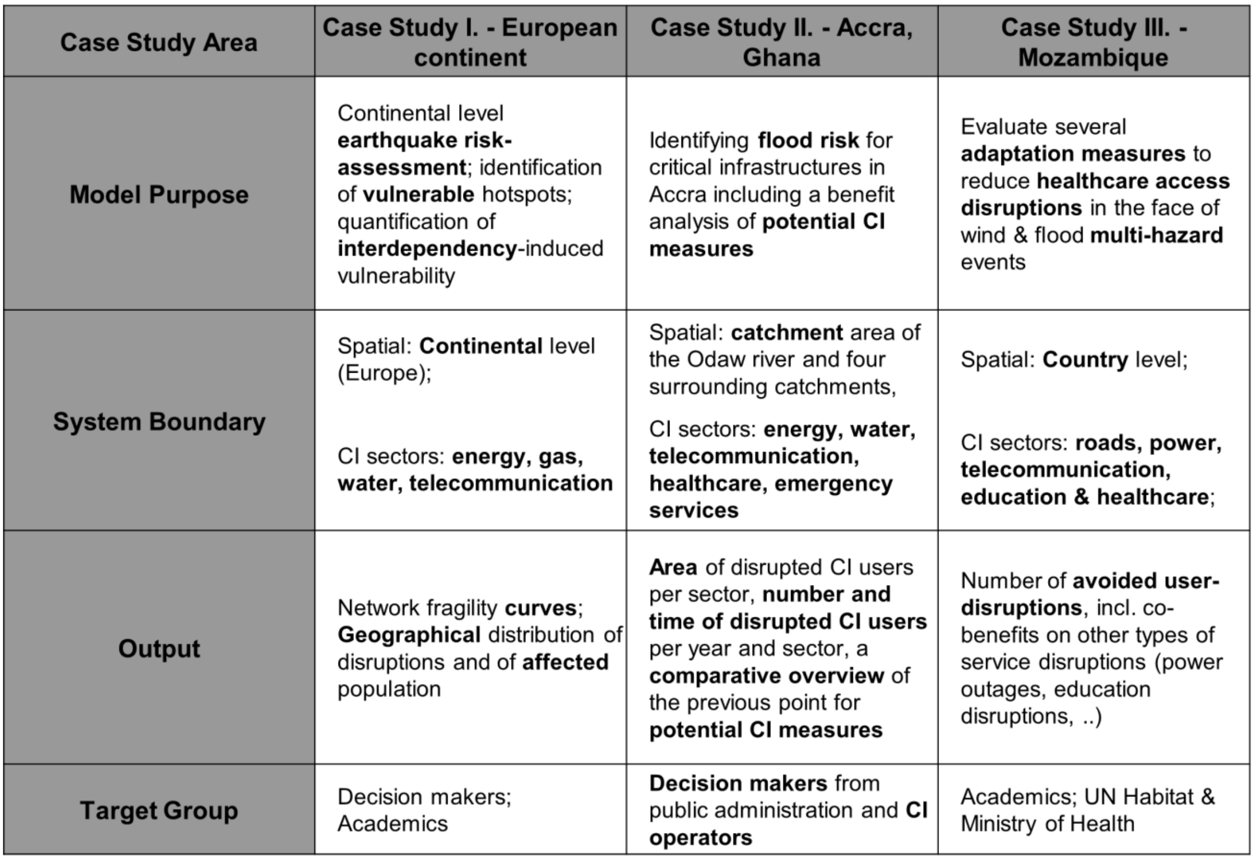
This chapter introduces a framework assembled from three elements to explore the implications of data scarcity on CI network models. First, three case studies are introduced and generalised based on their model purpose types. Second, the repercussions of data scarcity on the stages of a modelling workflow are identified for each model purpose type. Finally, the influence of data scarcity on the model characteristics is elaborated.

5.3.1 Introduction of Case Studies with Varying Model Purposes

Three specific case studies which represent the experience of the authors are used to discuss the effect of data scarcity on CIN models. The case studies are defined by the four model characteristics, model purpose, system boundary, output, and target group, as shown in Table 5-1.

Case Study I. concerns a continental-level earthquake risk assessment for Europe with the aim of identifying vulnerable geographical hotspots and quantifying the vulnerabilities induced by dependencies between CI sectors. It is further on generalised as an example for the model purpose type (A): *hazard hotspot assessment*. Similar case studies have been presented in the scientific literature (Verschuur et al., 2020). While CI networks are represented at the asset level, simplifications regarding the detailed structures of various networks are made. Similar simplifications are made regarding the ways in which the various CI sectors are connected and how their disruptions influence the population.

Table 5-1: Three exemplary case studies using CIN modelling featuring a wide range of model purposes, system boundaries, and outputs. Those case studies serve for the further examination of data scarcity implications on modelling qualities. Case Study II. (Schotten & Bachmann, 2023a), Case Study III. (Mühlhofer, Stalhandske, et al., 2023).



Case Study Area	**Case Study I. - European continent**	**Case Study II. - Accra, Ghana**	**Case Study III. - Mozambique**
Model Purpose	Continental level **earthquake risk-assessment**; identification of **vulnerable** hotspots; quantification of **interdependency**-induced vulnerability	Identifying **flood risk** for critical infrastructures in Accra including a benefit analysis of **potential CI measures**	Evaluate several **adaptation measures** to reduce **healthcare access disruptions** in the face of wind & flood **multi-hazard** events
System Boundary	Spatial: **Continental** level (Europe); CI sectors: **energy, gas, water, telecommunication**	Spatial: **catchment** area of the Odaw river and four surrounding catchments, CI sectors: **energy, water, telecommunication, healthcare, emergency services**	Spatial: **Country** level; CI sectors: **roads, power, telecommunication, education & healthcare**;
Output	Network fragility **curves**; **Geographical** distribution of disruptions and of **affected** population	**Area** of disrupted CI users per sector, **number and time of disrupted CI users** per year and sector, a **comparative overview** of the previous point for **potential CI measures**	Number of **avoided user-disruptions**, incl. co-benefits on other types of service disruptions (power outages, education disruptions, ..)
Target Group	Decision makers; Academics	**Decision makers** from public administration and **CI operators**	Academics; UN Habitat & Ministry of Health

The model purpose of Case Study II. is to identify the flood risk as population time disrupted per year for CIs next to other tangible flood consequences, such as economic damage and endangered populations. The analysis groundson a CIN model based on (Schotten & Bachmann, 2023a) and is additionally used to compare the benefits of potential mitigation measures and allow for improved decision-making. The specific model purpose of flood risk management could be generalised by applying it to other natural hazards, such as droughts, storms, and bushfires. Thus, it is generalised further on as model purpose type (B) *hazard risk management*. In terms of abstraction from the real complexity of CIN, this type is more differentiated with regard to the sectors than the first case study, but has a smaller spatial boundary.

The third case study is a sectoral adaptation study designed to decrease healthcare access disruptions across the population in the face of multi-hazard (particularly strong winds and flooding) events (Mühlhofer, Stalhandske, et al., 2023). The analysis is based on an integrated natural hazard risk and CIN modelling approach (Mühlhofer, Koks, et al., 2023) to evaluate five adaptation measures, which are either focused on resilience-enhancing measures to a single CI type, target multiple CIs at once, or modify the dependency relationships among CIs. While real-world data are used to map the interdependent CI systems and hazards, the stylised parameterisation of adaptation measures exemplifies trade-offs and benefits of component level against system-level measure packages to prevent service disruptions. Due to the focus on one sector, this model purpose is generalised as type (C) *sectoral adaptation*.

5.3.2 Repercussions of Data Scarcity for Every Modelling Stage in the presented Case Studies

Exemplifying the introduced modelling stages of the derived modelling workflow (cf. section 5.2.1) and data requirements (cf. section 5.2.2) on the presented case studies (cf.

Table 5-2: Repercussions of data scarcity in every modelling stage, illustrated for three different model purpose types A, B, C, generalised from exemplary case study experiences in Table 5-1. Bold writing indicates the general aspect of interest, italic writing elaborates on the deficit of the input data and the normal

Model Purpose Type	**(A) Hazard Hotspot Assessments**	**(B) Hazard Risk Management**	**(C) Sectoral Adaptation**
(1) Mapping of Infrastructure Assets	**Network structures** *Only partial information available.* Several assets of the examined networks may be missing or not correctly placed, introducing some uncertainties in the results.	**Network structure of electricity grid** *Only substation information available.* Coarse granularity of electricity sector causes inaccurate results because electricity transformers are not represented.	**Healthcare sites and types** *Many unmapped healthcare sites, unclear service offerings.* Faulty baseline system.
(2) Quantification of Dependencies	**Connections or dependencies between infrastructure** *No information regarding connections.* Assumptions made during this stage introduce some uncertainties in the results.	**Redundant connections in between nodes** *No information about redundancies.* The disruptions in the CIN model will be overestimated due to missing redundancies.	**Dependencies between power network and healthcare network** *No information available regarding the extent of dependency on the power sector.* The disruptions in the CIN model will be overestimated due to overestimation of healthcare site dependencies on the power grid.
(3) Quantification of CI Services	**Population served by each considered asset** *No available information regarding detailed numbers of population served.* Only estimations of population affected are possible.	**Metrics to quantify CI sectors in multi-sectoral network** *Not all sectors give the same metric for CI disruption.* Results of the multisectoral CIN model cannot be compared with each other.	**Socio-economic constraints to access healthcare services.** *No available high-resolution information on who is (financially) able to seek healthcare support.* Over/under-estimation of potentially impacted population.
(4) Impacts of Natural Hazards	**Earthquake damage-functionality relation** *Difficulty in obtaining detailed damage-functionality data for the considered assets.* Binary functionality considered via fragility functions, which may differ from real infrastructure response.	**Water depth-functionality relation** *No data or information for the range of sectors available and the area of interest.* The water depth - functionality relation is set to be binary. Disruptions and their sensitivity might be overestimated.	**Parametrization of combined wind- and flood damage - functionality curves for infrastructures.** *No data on the effect of structural damage onto the functionality of local infrastructures.* Binary and arbitrary damage-functionality thresholds for all infrastructure components may under/-over estimate impacts.
(5) Determination of Response & Recovery	**n/a**	**Recovery time of communication towers** *Sector specific recovery times from other survey areas are extrapolated to unsuitable case study areas.* Availability of spare parts differs in this area due to higher frequency of flooding events. The resilience of this sector is underestimated.	**Clarification on the availability of backup generators for response** *The presence of back-up generator and their associated start-up and run times is not available* Potential damages could be overestimated and potential measures could be suggested that might be in place already.
(6) Appraisal of Adaptation Measures	**n/a**	**Effectiveness of potential measures** *No knowledge about the applicability of a potential measure due to missing information about the technical set up of a CI element.* Measures are tested for effectiveness that might not be feasible at the selected network element.	**Applicability and cost of potential measures** *Unclear (financial) means, cost and local fitness for purpose of certain measures.* Measures may be not implementable, or not as effective as modelled.
(7) Validation, Calibration & Plausibility Evaluation	**Documented failures for similar earthquake scenarios** *No available data at the level of examined detail.* Accurate model validation is not possible.	**Area of disrupted people during historic events** *Not available only individual experiences or anecdotal stories.* No Calibration of model parameters possible.	**Documentation of historic events along the entire impact chain.** *Limited availability of exact hazard footprints, structural damages, functionality failures, service disruptions.* Only anecdotal validation or plausibility valuation, no calibration possible.

section 5.3.1), Table 5-2 briefly illustrates typical repercussions of data scarcity for the corresponding three generalised model purpose types: Type A as hazard hotspot assessment (Case Study I.), Type B as hazard risk management (Case Study II.) and Type C as sectoral adaptation (Case Study III.). Table 5-2 does not claim that these specific repercussions always occur for the associated generalised model purpose types. It merely serves to highlight that this is one of the possible repercussions that can occur and suggests a way of expressing repercussions for a model. For brevity, only one instance of lacking data and its consequence for the modelling process is discussed per stage and case study. Additionally, it is noted that the three given model purpose types are not a complete picture of all possible model purpose types but only three possibilities. A brief overview is given in Table 5-2 for each modelling stage. In the asset mapping stage, all case studies receive incomplete or partial information about specific CI sectors. This leads to a coarse representation of the network and its sectoral hierarchy, as well as a higher uncertainty of the results. In the stage of dependency quantification, the general issue is missing information about dependencies. This materialises in assumptions that need to be made and overlooked redundancies that should not be disregarded. For the stage of quantification of CI services, the level of detail of the input necessary for specific model purposes is a challenge. An additional challenge is to retrieve the same metric for different CI sectors, resulting in challenges for the comparability of scenario calculations.

For all case studies, different problems occur in the stage of natural hazard and operational limits, and the types of challenges are determined by the model characteristics. The first case study (Type A) mentions that no functionality-impact relation is available for earthquakes. The second case study (Type B) is missing sector-specific flood-depth-functionality relations, and the third case study (Type C) is missing a combined flood depth and wind speed functionality relation. All missing information results in assumptions that lead to potential over- or underestimation of the final results. In the response and recovery stage, desired metrics are missing to quantify the recovery after a CI disruption. However, initial information about the mere presence of emergency structures is also missing, and thus, the response is not represented appropriately. In the measure appraisal stage, the issue concerns identifying potential measures alone. However, if these measures are identified, as in the second case study, the metrics to quantify the potential costs are missing. In all three case studies, the validation stage was strongly influenced by data availability.

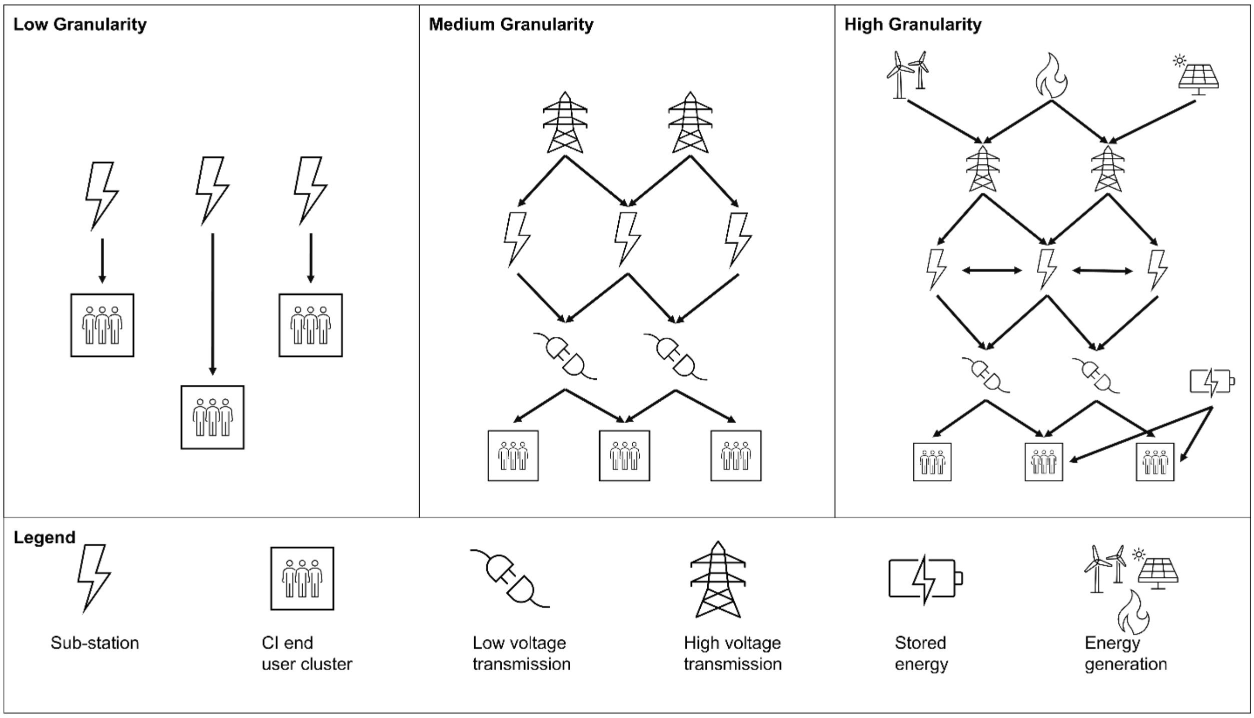


Figure 5-2: Amount of data and information available affects the resolution (granularity) with which CIs, CI dependencies, and services can be modelled.

5.3.3 Influence of Data Scarcity on Critical Infrastructure Network Model Characteristics

As the compilation in Table 5-2 illustrates, the absence of data impacts the model inputs and potential outputs. This invariably affects a range of model characteristics that should be evaluated to critically reflect their fitness for the intended purpose. Without a claim of completeness, a few crucial model characteristics and the implications of data scarcity on those are discussed below, extending the mathematically driven characteristics of networks, as introduced by (Arosio et al., 2020).

Granularity describes how fine or coarse a network model resembles the details of CI supply systems. Figure 5-2 illustrates one possible scale, from low to high granularity, for the electricity sector. The figure does not depict the exclusive approach to coarse granularity; for instance, the dynamics encompassed by coarser granularity can also be cross-sectoral. Granularity is intricately linked to the accuracy and complexity of CIN models. Invariably, the amount of data and information available influences how accurate and complex a model can be and how granular it may or should be resolved. The granularity is adjusted on a precision scale according to the model objectives. Thus, Type A models tend to attain their model purpose using coarser granularity than Type C models, which may generally require finer granularity. The comparison of examples in cells 1A and 1C can also be seen in Table 5-2.

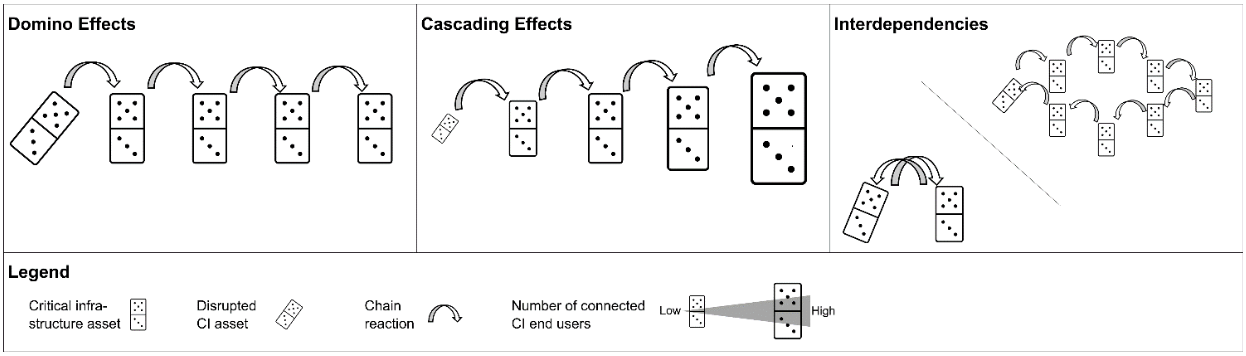


Figure 5-3: Types of failure mechanisms or chain reactions that can propagate through disrupted CINs adapted from the definitions by the German Federal Office of Civil Protection and Disaster Assistance (BBK). Depending on data availability, different failure mechanisms/chain reaction types may be captured.

Another CIN model characteristic linked to granularity and accuracy is its *ability to resemble chain reactions*. The German Federal Office of Civil Protection and Disaster Assistance (BBK) suggests a scale of three types of chain reactions, as shown in Figure 5-3 (German Federal Office of Civil Protection and Disaster Assistance (BBK), 2023). The first type of chain reaction refers to the *domino effect*, in which disruptions are propagated through critical infrastructure assets through their dependencies. *Cascading effects* describe a type of chain reaction similar to the domino effect, but underline the progressive consequences of the disruption. The last type of chain reaction features *interdependencies*, which refer to mutual reliance or connections between different CI assets. Depending on the granularity as well as the level of detail of the dependency information, these different chain reaction levels are representable in CIN models. Table 5-2 introduces in cell 2A the fact that all those dependencies had to be assumed and thus have a lot of uncertainty. Thus, the resemblance of chain reactions may be inaccurate.

The *communicability* of CIN models describes their ability to transfer their methodology and potential outputs to the desired target group. The absence of information and data often leads to replacement through assumptions and heuristics, which often occur implicitly or may not be closely tracked. More assumptions may lead to lower communicability of how a model is set up and reduce trust in its output. This is one factor influencing the process of testing measures in the CIN model environment, as described in Table 5-2, cell 6B.

The existence of many assumptions due to data scarcity may hamper *the reproducibility* of a modelling approach by other researchers. Furthermore, data availability and assumptions for certain geographic or system boundaries for which a model was initially designed may not extend to other regions and systems, limiting its transferability. Some modelling approaches may be more versatile and flexible with respect to underlying premises than others, which feature a higher level of hard-coded assumptions, or which are calibrated against specific, non-widely available datasets.

5.4 Discussion and Outlook

Current CIN modelling techniques can already supply advice for consequence assessment and mitigation planning; however, the more accurate, complete, relevant, consistent, and accessible the data, the better the model results. The added value of this study lies in collecting the data requirements of the CIN models. This is achieved through the systematic division of data categories and associated data types based on the modelling stages. Further possibilities of categorisation, for example, based on sectors or importance for models, are conceivable. These new categories have the potential to elicit additional data types that have not yet been considered. Therefore, this work does not claim to be a complete collection of data needs, but intends to promote the data availability of CIN models.

Wording remains a challenge in the field of hazard modelling because impact modellers and CIN modellers do not share the same established terminology. Although the network models considered in this work have been limited to graph-based CIN models, identifying the right terminology for the interaction between data scarcity and CIN models remains an issue. The previously defined characteristics are the first approach to describe the interface of these fields under consideration of the capabilities and limitations of CIN models. More efforts need to be invested in defining a generally accepted terminology for a range of network characteristics such as fidelity, granularity, sensitivity, or the representation of cascading effects to close the gap between impact modelling and CIN modelling.

In the context of this study, the category of CIN model purposes has been defined and filled with three examples along a scale from (1) hazard vulnerability hotspot assessment to (2) hazard risk management to (3) sectoral adaptation. These examples seek the representation of network models on a scale comparable to the spatial scale (global, national, regional, and local) suggested by (de Moel et al., 2015) for flood risk assessments, including typical model characteristics for each scale level. In the future, scales such as these need to be defined for other CIN model characteristics with a clear division of levels. The definition of these levels is not about setting a better or worse value but about being able to accommodate the subdivisions defined by model purposes and enable differentiation of the characteristics.

Assumptions made by CIN modellers are one concomitant of data scarcity. These assumptions can be supported by CI operators and scientists alike through expert knowledge. Nevertheless, assumptions influence the performance characteristics of the network model. Although commonly used in CIN models, current studies often lack sufficient communication or quantification of the uncertainty resulting from assumptions, unlike other fields in which such practices are more prevalent (Winter et al., 2018). A range of possibilities are available to modellers to quantify or counter uncertainties, beginning with uncertainty analysis (Tabandeh et al., 2022), sensitivity analysis, anecdotal verification with expert knowledge, or at least an overview of made assumptions, as done in (Mühlhofer, Koks, et al., 2023). Uncertainty and sensitivity analyses often rely on more input data, for instance, forsetting modelling parameters. How to validate, verify, or make plausibility checks of modelling parameters appropriately remains an open question. These checking processes can be performed in many possible ways, from surveys validating each asset and its characteristics, to the validation of small representative units of a network, to the anecdotal validation of individual elements of a CIN, and under consideration of the temporal variability of data inputs. It is suggested to further investigate CIN model validation techniques based on specific model purpose types and under consideration of the data needs highlighted in this study.

Communication and the expressed quantification of uncertainties have the potential to enhance trust in CIN model results and, consequently, strengthen CIN modelling methods as a whole. When it comes to presenting results, uncertainties must be communicated appropriately to establish trust with the intended recipients and allow for robust decision making (De Kleermaeker & Verkade, 2013). In the case studies presented, CI stakeholders, particularly CI operators, were involved as recipients in the development and implementation of measures. In any case, trust is significant in ensuring sufficient eagerness. Early and ongoing participation of CI stakeholders in the process of CIN hazard assessments can be beneficial in all stages of the modelling process (de Bruijn et al., 2019; Murdock et al., 2018). Not only will this create a greater identification in the potential results, but it also has a huge potential of acquiring qualitative information or sometimes even quantitative information, in perspective: data. Limited resources for the participation of CI stakeholders and the acquisition of input data should be adapted to the model purpose intended to be addressed with a model. It is important to ensure that all other model characteristics are aligned with the needs of the affected CI stakeholders to enable mutual benefits.

An issue that persists and needs to be addressed in participatory settings is the way data are conveyed or provided. A range of options has been tested by the US Federal National Laboratories (for example, Sandia Lab, Los Alamos Lab, Idaho National Laboratories), but the knowledge is not publicly accessible for security reasons. Opposite to these options is the openness to share most of its infrastructure data, as done in New Zealand for example (Zorn et al., 2020). Therefore, it seems that the willingness to share data varies greatly, and discussion is ongoing. The question remains whether the sharing of data or information itself is proven to cause more disruptions in CIN owing to physical or cyber-attacks compared with disruptions from natural hazards that cannot yet be recorded or recorded inadequately owing to a lack of data exchange.

Although some data sources were compiled in this study, gaps remain. The framework presented addresses how to encounter data scarcity in the surroundings of CIN models and puts the interpretation of the thus-created results into perspective. This framework does not deliver a strategy for overcoming data scarcity. Solicited strategies need to be considered, such as the collection of more impact data in the direct aftermath of disaster events, either in person or through social media. Another suggestion is to establish accessible CIN datasets or platforms for research, including a range of prerequisites from users and providers: (1) consideration of previously defined data types needed, (2) awareness of the level of detail that needs to be published if this data is used by CIN modellers, and (3) sensibility for privacy of CI users. Despite the strong case for more and better data and information in CIN modelling, it is paramount to critically reflect on the need for complexity and detail, depending on the purpose for which a model is built. In many cases, the unavailability or inaccessibility of detailed data does not hamper the purpose of the developed CIN models. Whether a model aims to create new knowledge (models for understanding) or to create new capabilities within its user space (models for action) may require different levels of upfront data availability, because in the latter scenario, users may provide those themselves on-the-fly, as deemed necessary. Further, societal context and ethical uncertainties may influence data requirements - some societies and studied problems may require higher levels of resolution and certainty to justify action than others.

5.5 Conclusion

CIN modelling offers approaches to better assess and manage natural hazards and to enhance resilience. Data inputs limit and determine the value of CI modellers' "offerings" to specific assignments. This study identifies overarching similarities in the modelling process, defines eight stages, and associates each stage with data types. The typification of these data needs has been documented, and the potential data sources for all data types are pinpointed, or if unavailable, gaps are identified. Three purpose-driven classes of CIN models have been distinguished (hazard hotspot assessments, hazard risk mitigation, and sectoral adaptation study) and set apart from the pure size-driven classification (e.g. local, regional, national, and global). For the model purpose type, case studies of CIN models have qualitatively shown the influence of data scarcity and the resulting assumptions at each modelling stage. The previous activities funnel into a framework that allows modellers to explore the implications of data scarcity on CI network models.

This work has increased the level of understanding regarding CIN modelling and the difficulties faced by both CI operators and CI modelling experts alike. The modelling stages and data types defined enhance the possibility of communicating about data needs and assumptions in participatory settings. On the other hand, an orientation is provided for network modellers at an early stage of a model setup, including potential data sources. The framework presented encourages CIN modellers to actively deal with uncertainties in their methods by delivering examples on how data scarcity influences network characteristics. Finally, this contribution advances the potential of CIN models to be utilised mutually by research and practice.

This work enhances CIN modelling techniques by clearly outlining their data needs based on modelling workflow stages and identifying potential data sources or examples in practice or research. Ultimately, this strengthens methods for analysing urban resilience by incorporating CI services in analyses. The purpose of CIN models is to align with CI stakeholders and model characteristics.

6 SYNTHESIS

In the synthesis, the research objective and the research questionss are revisited, the results derived in each manuscript are presented, challenges and limitations are briefly discussed, and future research objectives and potentials are formulated.

6.1 Research Results

The main research objective as well as the supporting research questions presented in the introduction (cf. Section 1.4) are revisited in this section, and the results that were identified are briefly summarised based on the findings of the individual manuscripts.

The overall research objective of enhancing improved resilience of CIN during flood events to ensure more continuous service provision has been achieved through several key steps: defining a general FRM workflow that incorporates CI, developing a CIN modelling method tailored to FRM-specific needs, systematically collecting potential measures, and proposing risk-based decision-making matrices to support the selection of appropriate measures. Additionally, the implications of data scarcity for CIN considerations have been examined.

The dissertation effectively offers a method to address four out of the six key criteria for evaluating the significance of a disruptive effect as outlined by the CER Directive. It thoroughly explores the number of users dependent on the essential service, the interdependencies among sectors and subsectors, and the geographic scope of potential disruptions. Additionally, the study partially considers the duration and extent of impacts on economic and societal activities, thereby enhancing the nuanced understanding of systemic risks in the resilience of critical infrastructure.

Subsequently, the research questions addressed in each manuscript are revisited and answered in detail, beginning with the first manuscript presented in Chapter 2:

1. **Schotten, R., & Bachmann, D. (2023b). Integrating Critical Infrastructure Networks into Flood Risk Management. *Sustainability*, *15*(6), Article 6. DOI: /10.3390/su15065475**

1.a) What has been done so far to integrate CI into the individual steps of FRM?

A wide range of literature was identified that addresses individual steps of flood risk management (FRM), beginning with the analysis, assessment, and management of risk with measures. For FRA, network modelling approaches have been identified that enable consideration of the individuality of CIN and form the basis for the future modelling approach (Pant et al., 2018). Additionally, state-of-the-art FRM approaches, which quantify flood risk in terms of economic damages or human impacts by considering probability (Bachmann, 2012), have been identified and served as the foundation for the desired integration of CI. For the assessment stage, but also in support of the other stages of FRM, participation methods that encourage communication with CI stakeholders for risk management have been identified (de Bruijn et al., 2019; Greiving et al., 2021). These participatory approaches have been recognised as having high potential to benefit the entire process. The consideration of measures in this approach has been outlined as important during the literature review but has rarely been considered in many integration processes (Ani et al., 2019). The foundation was laid under consideration of this literature and more to pursue objective 1.b).

1.b) How could a comprehensive approach be shaped to incorporate CI into each step of FRM?

The incorporation of CI into FRM was accomplished by examining each step of the FRM process and specifying instructions on how to integrate CI at each step. A CIN modelling approach was utilised in the FRA stage, enabling the consideration of critical infrastructure consequences. This encompasses sectoral and intersectoral cascading effects, quantifying CI service disruptions as population time T_{Pop} (cf. Equation 2-1), and information on the areal spread of CI network disruptions. Next, the CI flood risk per year R_{CI} was developed by considering the hydrological probability in combination with T_{Pop} (cf. Equation 2-2). Other metrics are developed during the FRA step in the form of network characteristics, such as *cascade potential value* and *cascade vulnerability value*, integrating information about vulnerable and influential CI elements in flood-prone areas. The next step of FRM, the decision to accept or reject a flood risk situation, has been extended to include CI-specific stakeholders, making it accessible based on the data and metrics previously established. The topic of communication was integrated into FRM as an essential component, tailored to the significant interdependencies among CI operators, and a method was developed to ensure continuous engagement. This continuous engagement has been shown to benefit all stages from FRA, decision-making regarding the flood risk situation and the development of measures. Research question 1.b) is addressed by demonstrating that the implemented integration expands risk-based decision-making options. This approach offers a more accurate estimation of flood risk by incorporating consequences typically overlooked in current FRM practices.

1.c) Can the proposed approach be proven to improve FRM in a case study?

The benefits of integrating CI into FRM were demonstrated through a case study in Accra, Ghana. A CI network model was utilised to derive T_{Pop} and R_{CI} for CI across six sectors, proving the potential to complement FRA. The CI network characteristics aid in identifying risk reduction measures that are successfully implemented in model scenarios and are compared to the initial state of the study area using a decision-making matrix. Ongoing participation of CI operators and stakeholders has proven beneficial, for example, by showing an increase in data input before and after participation. In conclusion, the effective integration of CI into FRM is validated and ready for practical implementation, and particularly effective where collaboration between CI operators and FRM exists.

2. Schotten, R., & Bachmann, D. (2023a). Critical infrastructure network modelling for flood risk analyses: Approach and proof of concept in Accra, Ghana. *Journal of Flood Risk Management*. DOI: /10.1111/jfr3.12913

In chapter 3, the work of the second manuscript was presented, and three research questions were addressed here:

2.a) What are the most effective approaches for modelling the functionality and service of CIN?

To investigate research question 2.a) CIN modelling approaches were examined based on well-established literature (Ouyang, 2014; Rinaldi, 2004). Different types of network modelling approaches such as agent-based, system dynamics-based, flow-based or network-topology-based were inspected in a literature review to identify a suitable approach for the integration into FRM. The most suitable modelling approach were evaluated depending on delineating and defining the modelling requirements for FRM. Therefore, thematic or sectoral constraints were clarified as the framework for this research objective. This includes, among others, the exclusion of the transportation sector and the omission of linear infrastructure elements in general, such as roads, power, and cable lines. At the same time, the modelling approach should adequately represent cascading effects based on physical, logical, or logistical dependencies, without requiring the highest level of accuracy, and must be representable in a topology-referenced network.

2.b) Which modelling approach of CIN is suitable for a flood risk analysis in FRM?

The research question 2.b) was addressed by practically documenting and implementing a modelling approach. The modelling approach was introduced as a CIN module in the FRM modelling software PROMAIDES (Bachmann, 2023). The objective of the modelling approach is to quantify multisectoral CI service disruption by flood events on a regional scale. It is a combination of a high-level architecture to account for layered systems-of-systems in CI networks (Pant et al., 2017) and a network topology-based approach to account for the fact that network elements must be considered in their geographical location. Three model elements are used to define the network model: 1) Point elements represent infrastructures and contain attributes such as the water level they can withstand without service interruption, or the recovery time required for the infrastructure to become fully operational after a disruption. 2) Polygon elements represent the number of end users supplied by a CI service. 3) Connector elements link point and polygon elements to indicate dependencies. In addition to the operation of the CIN module, data inputs for this method are thoroughly detailed.

Given the necessity to build highly complex and extensive network models, descriptive network metrics are important to isolate information from the model. Established CI network characteristics, such as the hub value H, which counts the number of outgoing connectors per point element, and the authority value A, which counts the number of incoming connectors per point element, were used. Two new metrics were also introduced to complement these existing ones: the cascade vulnerability value and the cascade potential value. Overlaid with flood maps, CI network models deliver both direct and indirect disruptions within and across sectors owing to cascading effects. The results from each time step of the CI network interaction with the flood map were also made available.

This modelling approach allows the users to balance between replicating the reality of CI networks and the level of detail required for improved FRM. The straightforward structure comprising three types of CI elements accommodates a range of complexities, from basic designs with few elements to intricate multi-sectoral, multi-layer models. As such, the developed modelling approach is flexible and can adapt to the precision of the available data coverage and the specific interests of stakeholders.

2.c) How can this modelling approach be applied in a flood risk analysis?

The CI network modelling approach of the CIN Module is applied as a proof-of-concept for the Odaw catchment in Accra, using data from publicly available data sources. These data sources as well as the preliminary results were validated using two levels of stakeholder engagement. First, individual exchanges with representatives from each sector were initiated, and second, in a participatory setting where all CI stakeholders came together was hosted. A flood risk matrix was derived for Accra, including flood consequences for people and economic damage. This was supplemented with CI disruptions from the CIN model. Furthermore, it has been demonstrated that disruptions to CI can extend beyond the catchment area of the Odaw river. The derived consequences for the CI were then shown to be reduced with a range of measures. Overall, the CIN module and its modelling capability showed its applicability in this proof-of-concept and helped facilitate the integration of CI networks and their disruptions into flood risk management protocols.

In Chapter 4, the work of the fourth manuscript was presented, and three research questions were addressed here:

3. Schotten, R., & Bachmann, D. (2024). Cataloguing and Testing Flood Risk Management Measures to Increase the Resilience of Critical Infrastructure Networks . *Smart Cities,* Accepted 11.10.2024.

3.a) Which flood risk reduction measures can be considered for different CI sectors?

The research question 3.a) was replied to by reviewing the literature and conducting interviews with CI experts, resulting in the compilation of a catalogue of flood measures specific to CI. The catalogue was divided into five CI sectors as well as the stage of the DRR management cycle (cf. Figure 4-1). Generalised trans-sectoral measures were derived in an extra category from the sector specific measures.

3.b) How can a collection of flood measures tailored to CI, support the integration of CI into FRM?

The catalogue serves as a tool to advance CI network case studies towards the implementation phase by proposing practical measures (cf. Appendix 1). Categorisation along the DRR cycle allows for the identification of measures depending on the stage to be confronted with measures. At the same time, the catalogue's measures help gauge the applicability of CIN modelling approaches: the more measures can be considered in a model setup, the more applicable and valuable the modelling approach for FRM.

The presented case study of the relatively small Vicht catchment in West Germany provides proof-of-concept for the application of the measure catalogue. The effectiveness of the measures could be checked, a significant reduction in the affected population could be proven for the catchment area, and the overall resilience of the CI network increased (cf. Table 4-7).

The fourth and last manuscript is introduced in Chapter 5, and delivers the answers for the following three research questions:

4. Schotten, R., Mühlhofer, E., Chatzistefanou, G., Bachmann, D., Chen, A., & Koks, E. (2024). Data for critical infrastructure network modelling of natural hazard impacts: Needs and influence on model characteristics. *Resilient Cities and Structures*, *3*, 55–65. DOI: 10.1016/j.rcns.2024.01.002

4.a) What data requirements are necessary for risk modellers to analyse the consequences of natural hazards in general?

To address research question 4.a) similarities in the CIN modelling process were identified collaboratively and delineated in eight stages to form a generalised modelling workflow. The data requirements were recorded for each stage, and the associated data types were defined.

4.b) How can data scarcity be effectively addressed and mitigated?

The challenge of addressing data scarcity, as outlined in research question 4.b) was addressed by compiling a collection of available data sources. This initiative aimed to enhance communication regarding this challenge and urge modellers to acknowledge the uncertainties inherent in their methods and data.

The definition of data types and modelling workflows has deepened the understanding of CIN modelling, and the challenges encountered by CI operators and modelling experts. The delineation of modelling stages and data types improves the basis for the communication of data requirements and assumptions in participatory settings. Additionally, the advocated framework defines a basis for CIN modellers to proactively address uncertainties in their methods by illustrating how data scarcity affects network characteristics. Ultimately, this study enhances the applicability of CIN models for research and practical purposes.

4.c) What are the implications and potential impacts of data scarcity on the analysis process and outcomes?

The implications of data scarcity were shown for three purpose-driven categories of CIN models (hazard hotspot assessments, hazard risk mitigation, and sectoral adaptation studies). These have been identified previously from case studies and were an attempt to distinguish it from a purely spatial-extent-based classification (e.g. local, regional, national, and global) (de Moel et al., 2015). Additionally, case studies were used to show the consequences of data scarcity on performance and the resulting assumptions at each modelling stage.

6.2 Challenges and Limitations

A brief summary of the most relevant challenges and limitations is provided below. The lack of connection between FRM and CI operation is the primary challenge, as indicated in some interviews conducted for the manuscript presented in Chapter 4. CI operators tend to have little capacity and are burdened by maintaining the status quo of their supply networks. Awareness and collaboration among CI operators can be improved, and integrated FRM provides a potential stage for such collaboration. Preparing for flooding can also be advantageous during other crises.

The presented dissertation focuses on critical infrastructure rather than on the representation of critical entities, which encompass a broader spectrum of aspects within the domain of critical services. Specifically, the systemic risks of flooding to governmental institutions are addressed only in a limited capacity—such as their role as recipients of electricity or ICT services, which may be disrupted by cascading effects. However, the risks stemming from the potential failure of governmental institutions themselves are not represented in this work.

This study limits itself by contributing to knowledge insofar as it does not aim to derive an assessment of flood risk for Accra or Ghana in general. From the outset, this objective was not defined as part of the research objective. Additionally, no supplementary flood risk assessment was conducted, primarily due to the lack of consistent involvement and commitment from decision-makers within critical infrastructure organisations. A closer collaboration with representatives of these organizations would have been necessary to move beyond anecdotal validation of input and output data.

Triggering more active FRM is not only a matter of capacity but also of cost effectiveness. The pricing of services provided by CI operators cannot always consider resilience-enhancing and risk-reduction measures or lack a translation of such measures towards fiscal decision making (Committee on Climate Change UK, 2014). This limits the application of the present study. Nevertheless, financial institutions and legislation are actively pushing for methods to connect FRM with CI services under the consideration of cost-benefit calculations (European Commission, 2024; World Bank Group, 2018). The presented work provides a method to measure flood risk reduction effectiveness, aiding in determining the value created and the consequences for critical infrastructure. This enhances resilience by offering robust data for funding discussions.

The measures that could be incorporated in the modelling approach were limited, by the modelling approach and sufficiently accurate quantifications of the measures. Quantifying organisational measures, aside from recovery speed, presents a notable challenge for the modelling approach presented in this dissertation. This becomes apparent when attempting to implement all the measures in the model environment in Chapter 3. Accurately quantifying the impact of these measures remains a challenge. The CI operators interviewed struggled with this due to the highly individual nature of flood risk reduction measures for their infrastructure environment. Assumptions were necessary in the proof-of-concept modelling to quantify the effects on the recovery time and water level threshold. While these assumptions add uncertainty to the model output, it is still preferable to incorporate them, even amidst uncertainty, rather than disregarding them entirely.

Each model represents the real-world conditions in a simplified manner. Therefore, the ability to represent measures also reflects the maturity of the modelling approach. The modelling approach has intrinsic assumptions, such as the binary failure state of the CI elements. This leads to the coarse representation of reality in the CIN models. The refinement of the modelling approaches can help better represent real-world conditions. Even though the representation of flood velocity in damage modelling for economic consequences is not recommended (Kreibich et al., 2009), damages to the critical infrastructure in the Ahr Valley in West Germany during the flooding 2021 reveal a relationship between velocity and infrastructure damage, especially to linear infrastructures parallel to the flow direction, such as streets, canals, and wiring. Another limitation to address in the overarching context of this work is that the proof-of-concepts in each manuscript and thus the entire dissertation, focused exclusively on the primary sectors of energy, ICT, and water. This narrow scope was chosen for two reasons: first, to delimit the field of application for this study, and second, because the modelling method is less suited to representing linear structures, which resulted in a very limited consideration of the transport and traffic sector.

In addition to intrinsic model assumptions, extrinsic factors limit the accuracy and applicability of the modelling approach. The CI network modelling approach presented in this dissertation, mainly in Chapters 2 and 3, suggests resembling real CI networks based on logical and physical dependencies of CI elements. Intrinsic model uncertainties arise primarily from two factors. First, uncertainties stem from the quality of the raw input data (such as localisation accuracy, structural extent, dependencies among CI elements, recovery durations, water depth thresholds, and population count per polygon) with regard to homogeneity across the area of investigation and the granularity of the CI systems. Second, uncertainty enters the model with the transformation of the raw data into model input data, for example, the use of Voronoi polygons as a nearest-neighbour assumption for the connection of CI elements or the derivation of CI element attributes from individuals to all elements. Both types of uncertainties must be communicated to decision makers when presenting the results, but can also be improved significantly by including CI stakeholders in the process (de Bruijn et al., 2019; Murdock et al., 2018). This early involvement also triggers the trust of CI operators in the results and increases the chance of applying this methodology in practice.

6.3 Future Research Objectives and Potentials

A handful of challenges remain unaddressed in this work, although they are collected in this subchapter for future consideration. First, it is recommended to shift the application of the presented work into practice by approaching infrastructure operators or, more specifically, associations representing the combined interests of CI operators. In view of the national legislation following the Critical Resilience Entities Directive of the European Union, this has huge potential for application.

Therefore, a case study that summarises the untapped research fields of this dissertation is outlined further. The individual points addressed here can also be viewed as independent of each other. It is recommended to form a collaboration with at least three dedicated CI operators from different sectors (e.g. electricity, internet and communications technology (ICT), freshwater, wastewater, and gas supply services) in a common area of interest including a significantly high flood risk. Examples for collaborations with individual sectors have been provided by Pant et al. (2018) or Emanuelsson et al. (2014). Comprehensive collaboration with representatives from multiple sectors is still pending. Finally, it is recommended for future case studies to define spatial analysis units for various sectors and subsectors based on organisational boundaries. This method will be more practical for identifying and prioritizing measures than relying on subjectively defined buffer zones, as was done in the case studies of the presented manuscripts. Such an approach would enhance the objectivity and comparability of the proposed method, but also spark more interest by the organisations operating CI."

As a basis for this collaboration, a common data exchange platform should be formed that stores incident-based data to a degree of precision that allows adequate representation of the CI networks as well as its user connections, while simultaneously taking privacy and commercial interests into account. In addition to the previously listed attributes (cf. Chapters 3 and 5) continuous flood-depth-functionality functions for CI elements should be compiled collaboratively, as done by Koks et al. (2022).

After data gathering and model compilation, it is recommended to host a documented discussion about uncertainties as well as decisions that can be made based on the outcome. To further investigate the potential of measure inclusion, it is also recommended to associate the outcoming metrics, such as Population Time T_{Pop} and Risk for Population Time Disruption R_{CI}, with the potential costs of measures. Once the first iteration of model-build and measure consideration has been achieved it is recommended to further include climate change scenarios as a boundary for the hydraulic model.

The extensive case study suggested above should also drive a continuous development of the modelling approach itself. It is proposed to incorporate a function that allows the model to account for the gradual disruption caused by flood events and the subsequent stepwise restoration of critical infrastructures. To achieve this, it is necessary to introduce a parameter representing the relative functionality of infrastructures (ranging from 100% operational to 0% inactive), as well as to account for the flood-depth-to-functionality relationship for point elements. An aspect that should be considered in future work of potential case studies is the differentiation of end-users affected by disruptions in critical services. This differentiation should be based on social vulnerability criteria, which influence the consequences of disruptions for individual needs and thereby enable an equitable assessment of flood risks for critical services.

Another question which can be addressed in the aftermath of this dissertation is the scientific exploration of the argument that sharing critical infrastructure data is harmful. This counterargument attempts to discredit the method presented in this dissertation. However, the question remains whether sharing data about critical infrastructure and its vulnerabilities may not be even more beneficial than harmful. In particular, many infrastructure datasets are publicly available (OpenStreetMap contributors, 2017). Therefore, it is recommended to explore, through scientifically conducted interviews, how this issue can be thoroughly documented and ultimately overcome.

Finally this dissertation has the potential to benefit the robustness of critical infrastructure facing an increasing thread of flooding, but also activates the potential of CI operators for more intense collaboration.

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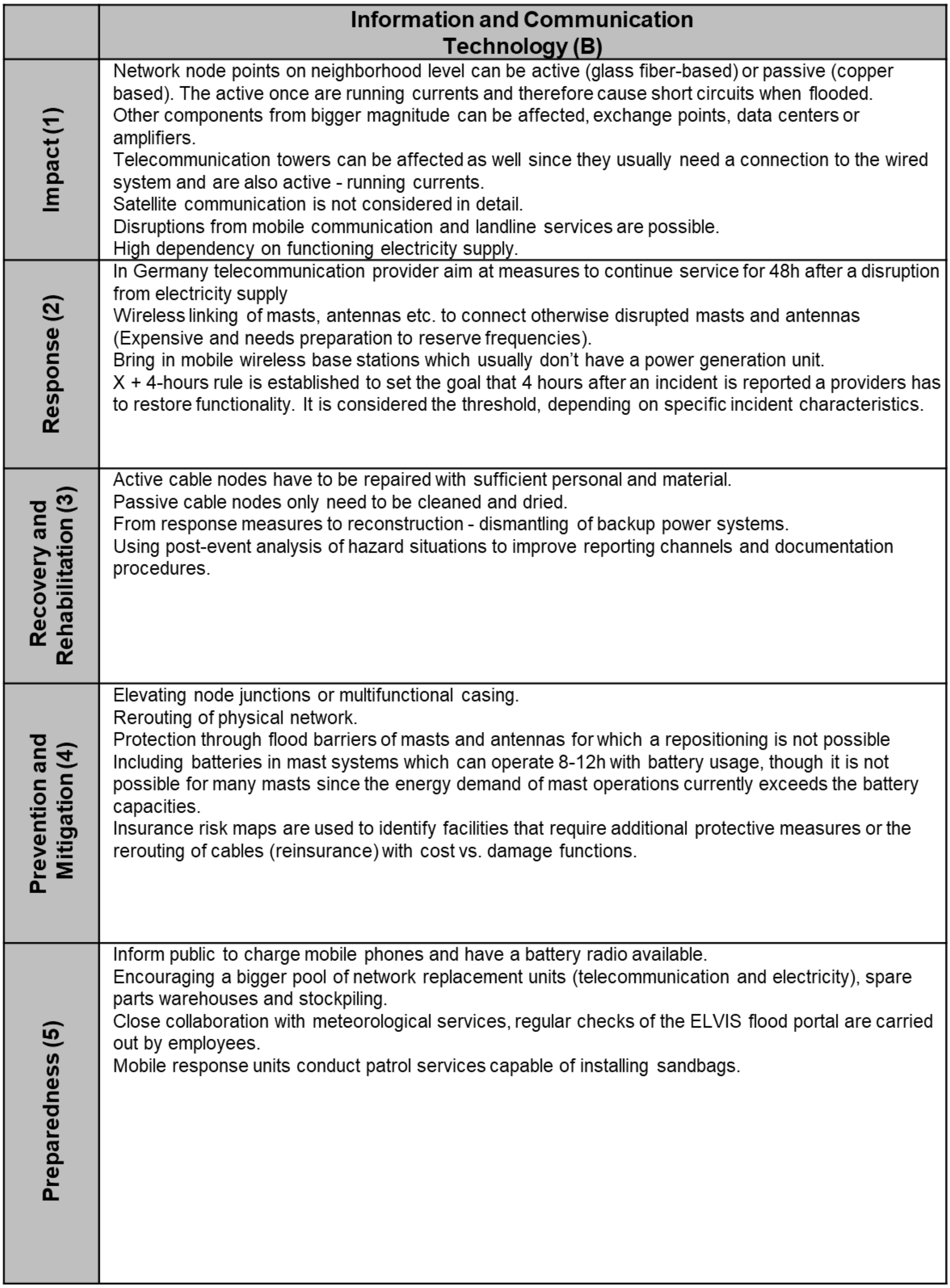
Appendix

Appendix 1A: Catalog of flood risk measures for a range of CI sectors and a generalized type.

	Electricity Generation and Distribution (A)
Impact (1)	Electricity and water are incompatible due to the high conductivity of water. The presence of water can compromise electrical insulation and increase the risk of electrical accidents.
Response (2)	Printout of network plans as a back-up option. Prioritisation of response measures in specific areas and for assets of prioritized customers. In the event of faults, maintenance personal has to automatically show up at the control centre. Establish possibility to connect emergency power systems for prioritised consumers. Release or disconnection of transmission facilities... ...to prevent uncontrolled situations. ...to avoid fault current in installations that can be passed on to actually unaffected installations by parallel network routing.
Recovery and Rehabilitation (3)	Prioritisation of recovery measures in specific areas and for specific vulnerable infrastructures: Administration buildings, clinics, hospitals and old people's homes (possibly police). Provision of reserve capacities.
Prevention and Mitigation (4)	Culverting of supply lines instead of routing them underneath bridges. Flood adapted components: Pressurised water-tight cable entries, Oil-immersed transformer cooling systems which are usually waterproof. T100 as a boundary for construction of equipment or otherwise increase of facilities to T100 height + x Strategically placed mobile flood protection systems: flood defence walls, flood barrier systems such as the beaver system. Purchase and regularly check and operate standby power systems. Overlapping of service areas to decrease potential outages. Communication Back-Ups: Setting up a company radio system in the area of influence of grid operator; Regular training and use of the company radio system by employees; Acquisition of satellite radio to enable communication between different supply levels of the power supply network;
Preparedness (5)	Layperson-operable emergency equipment. Storing of spare transformers for each transformation level from highest voltage level, high voltage level and medium voltage level to the low voltage level. This can significantly reduce the recovery time after an event but also leads to buying of peak in case of a large-scale event. On the other side this leads to higher costs which are in case of no event not compensated and normal ongoing maintenance works are prevented monetarily. Sensitisation for decreasing availability - adaptation measure for potential affected populations Availability of sandbags and sand. Identification of particularly suitable properties for storage with sandbags. Preparation of information to share with public if needed. Prepare crisis management committee and personal. Define a permanently staffed disaster response team including: the provision of two rooms for communication as well as consultation and organization; the provision of food or the activation of such. Frequent preparation and training courses. Training on documentation communication and assembly protocols for legal responsibility. Printout of network plans as a back-up option. Stockpiling of mobile switchgear and emergency power systems.

Appendix 1B: Catalogue of flood risk measures for a range of CI sectors and a generalized type.



	Information and Communication Technology (B)
Impact (1)	Network node points on neighborhood level can be active (glass fiber-based) or passive (copper based). The active once are running currents and therefore cause short circuits when flooded. Other components from bigger magnitude can be affected, exchange points, data centers or amplifiers. Telecommunication towers can be affected as well since they usually need a connection to the wired system and are also active - running currents. Satellite communication is not considered in detail. Disruptions from mobile communication and landline services are possible. High dependency on functioning electricity supply.
Response (2)	In Germany telecommunication provider aim at measures to continue service for 48h after a disruption from electricity supply Wireless linking of masts, antennas etc. to connect otherwise disrupted masts and antennas (Expensive and needs preparation to reserve frequencies). Bring in mobile wireless base stations which usually don't have a power generation unit. X + 4-hours rule is established to set the goal that 4 hours after an incident is reported a providers has to restore functionality. It is considered the threshold, depending on specific incident characteristics.
Recovery and Rehabilitation (3)	Active cable nodes have to be repaired with sufficient personal and material. Passive cable nodes only need to be cleaned and dried. From response measures to reconstruction - dismantling of backup power systems. Using post-event analysis of hazard situations to improve reporting channels and documentation procedures.
Prevention and Mitigation (4)	Elevating node junctions or multifunctional casing. Rerouting of physical network. Protection through flood barriers of masts and antennas for which a repositioning is not possible Including batteries in mast systems which can operate 8-12h with battery usage, though it is not possible for many masts since the energy demand of mast operations currently exceeds the battery capacities. Insurance risk maps are used to identify facilities that require additional protective measures or the rerouting of cables (reinsurance) with cost vs. damage functions.
Preparedness (5)	Inform public to charge mobile phones and have a battery radio available. Encouraging a bigger pool of network replacement units (telecommunication and electricity), spare parts warehouses and stockpiling. Close collaboration with meteorological services, regular checks of the ELVIS flood portal are carried out by employees. Mobile response units conduct patrol services capable of installing sandbags.

Appendix 1C: Catalogue of flood risk measures for a range of CI sectors and a generalized type.

	Water Supply (C)
Impact (1)	Damaged or disrupted pumping stations cause pressure drop in the supply lines. This subsequently leads to the entry of foreign substances from outside into the pipeline system. Treatment plants are not prepared for additional pollutants that can be introduced by flooding. In case of flooding, well facilities near bodies of water (shore filtrate facilities) are damaged for an indefinite period.
Response (2)	Coordinated emergency meeting points and procedures in case of disturbance scenarios. Definition of a priority list for protection and replacement facilities. Mobile and stationary emergency power supply systems can restore either electricity or water supply in emergencies (generators, pumps, combined pump-power systems).
Recovery and Rehabilitation (3)	Ventilation and de-aeration at hydrants. Opening of closing sluices.
Prevention and Mitigation (4)	Locating water supply facilities out of areas likely to be impacted by flooding. Ensure possibility to connect emergency power generators for pressure boosting systems. Elevation of facilities and replacement facilities. Detachment from indispensable ICT dependency and training of the team for the handling of manual control measures. Digital infrastructure is only optional. Monitoring and remote control are connected to the internet but are not necessary for functionality. Redundancy can be strengthened by establishing connections between different supply networks that compensate for the disruption of procurement or treatment facilities.
Preparedness (5)	Emergency management teams should be staffed with CI operators. Preparation of communication channels as backups (satellite phones, internal communication networks, radio). Definition of measuring points for flood water depths or other factors important for the operator in advance. Stocking of sand, sandbags and the communication about their availability. Arrangement of object protection contractors for facilities. Clarification of access authorization for vehicles before a flood event.

Appendix 1D: Catalogue of flood risk measures for a range of CI sectors and a generalized type.

	Wastewater Treatment (D)
Impact (1)	Pumping stations for transferring wastewater fail (directly or due to power failure) - Wastewater reservoirs overfill and float in public places Process control system fails due to power failure or internet failure Backwater causes water to penetrate electrical components of the wastewater treatment plant Wastewater volume decreases by 50% in affected areas
Response (2)	Backup emergency systems Mobile deployment and activation of power generators and waster water pumps. Utilization of fuel reserves. Dispatching of flush-suction vehicles. Shifting communication to dedicated frequency networks. Creation of blackout plans, flood scenario checklists, and plan lists.
Recovery and Rehabilitation (3)	Prioritised draining of treatment plan areas and pump stations within the catchment area of treatment plant. Set-up of internal communication network and connection of process control room to landline. Restoration of electricity supply and opening manual flood barriers. Demand assessment and procurement of emergency power generators and pumps. Obtaining external capacities for the drying of electric motors for pumping stations. Overhauling of dirty pumps, electric motors, and control cabinets. Maintaining the operation of the pumping stations within the urban area until flooding or evacuation of the site/catchment area. Minimizing damages for the quickest possible resumption of operations.
Prevention and Mitigation (4)	Installation of backflow preventers. Positioning of fixed backup pumps in designated areas. Additional protective measures for facility buildings: Waterproofing, protective dikes, installation of barriers. Expansion and elevation of the medium-voltage system. Increasing availability of maintenance and repair staff by sensitisation for individual prevention and mitigation measures on individual level.
Preparedness (5)	Activation of manual backflow preventers.

Appendix 1E: Catalogue of flood risk measures for a range of CI sectors and a generalized type.

	Gas Supply (E)
Impact (1)	The gas supply sector has a strong dependency on the availability of information and communication for their operations. Some assets are depending on electricity supply. Piping systems itself are usually not affected during flood events. Other punctual structures are affected by inundation.
Response (2)	Timely activation of important service providers for the gas operators. Sending out prewritten texts or information to end users and network partners Demanding the electricity shut-off for endangered or impacted assets from electricity supplier. The gas pipelines function as their own storage. Disruptions in the supply structure can be compensated for a while through the remaining gas pressure in the system.
Recovery and Rehabilitation (3)	Drainage of affected pipeline sections at the lowest points using suction pumps, so called pipeline pigs or the inlet of gas under sufficient pressure. Inspection and control of special structures (e.g. ducts), measurement and control technology in all pressure zones Ventilation of affected network components.
Prevention and Mitigation (4)	Routing of pipelines not parallel to river flow directions. Placement of water construction elements and gabions to prevent scouring due to increased flow velocities. Segmentation of local networks through the regular installation of shutdown and control systems to minimize the impact of outages in a small area. Sufficient elevation or enclosurement of network assets. No or cautious placement of structures within flood prone areas.
Preparedness (5)	Preparation of scenario cases to train staff on services disruptions Storage of flood inundations maps which should be validated in adapted based on new events Obtaining special rights for operational response teams and their vehicles. Inclusion of gas supply sector in crisis management committees.

Appendix 1F: Catalogue of flood risk measures for a range of CI sectors and a generalized type.

	Generalized Measures(F)
Impact (1)	Inundation causes disruption to all punctual assets across all sector. The difference is the height that structures and withstand and the vulnerability itself. For the electricity and wastewater treatment sector the impact through flooding may lead to immediate health risk in the impacted areas.
Response (2)	Possibility to easily connect network replacement components to assets. Availability and staff for the installation of network replacement units (Generators, pumps, ICT systems). Technical maintenance staff gathers in predefined meeting points during disruptive events. Priority lists for response measures.
Recovery and Rehabilitation (3)	Priority lists for recovery measures.
Prevention and Mitigation (4)	Rerouting of linear structures to prevente routing along the river body or replacing punctual CI assets in flood risk areas. Elevating or protecting critical components of CI assets vulnerable to inundation. Placement of water construction elements and gabions to prevent scouring due to increased flow velocities. Increasing the number of connections to other network islands to better compensate service disruptions caused by high level impacts.
Preparedness (5)	Including CI operators in crisis management committees. Organizing the availability, operability of mobile flood defenses or sandbags. Previous communication with service providers with relevant during crisis response and recovery (security firms, technical contractors, administration of permits for maintenance vehicles e.g.) regarding capacities and access permissions. Regional networking of critical infrastructure operators to enhance readiness with backup systems and fuel reserves.

Curriculum Vitae

Professional Experience

09/ 2020 - 12/ 2023	Research assistant, University of Applied Science Magdeburg-Stendal, Workgroup Flood Risk Management
01/ 2018 – 07/ 2020	Researcher and advisor, Deltares, Institute for Applied Research, Delft, Department for Environment, Hydrodynamics and Forecasting

Academic Experience

09/ 2020 - 07/ 2025	Cumulative dissertation, RWTH Aachen University Doctorate in engineering (Dr.-Ing.)
10/ 2015 – 11/ 2017	Postgraduate Course, Technical University Dresden Diploma engineer - Hydraulic engineering (Dipl.-Ing.) – Diploma Thesis: Application of risk-based flood forecasting in the coastal urban area of Manila Bay, Philippines to support short term decision-making processes.”;
04/ 2013 - 09/ 2015	Studies of Civil Engineering, RWTH Aachen University, Bachelor of Science
07/ 2012 - 11/ 2012	Exchange semester, University of the Sunshine Coast, Australia
10/ 2010 - 03/ 2013	Environmental Engineering and Science, RWTH Aachen University

List of Publications

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Dedication

This work is dedicated to the resilience of those who live with and have lived with cancer, and to the unwavering support of those who stand by them on their journey.

Dieses Werk ist der Widerstandsfähigkeit derjenigen gewidmet, die mit Krebs leben und gelebt haben, sowie der unerschütterlichen Unterstützung derjenigen, die an ihrer Seite stehen auf ihrem Weg.