Is this resilient enough? Including users' acceptance levels into the critical infrastructure resilience assessment

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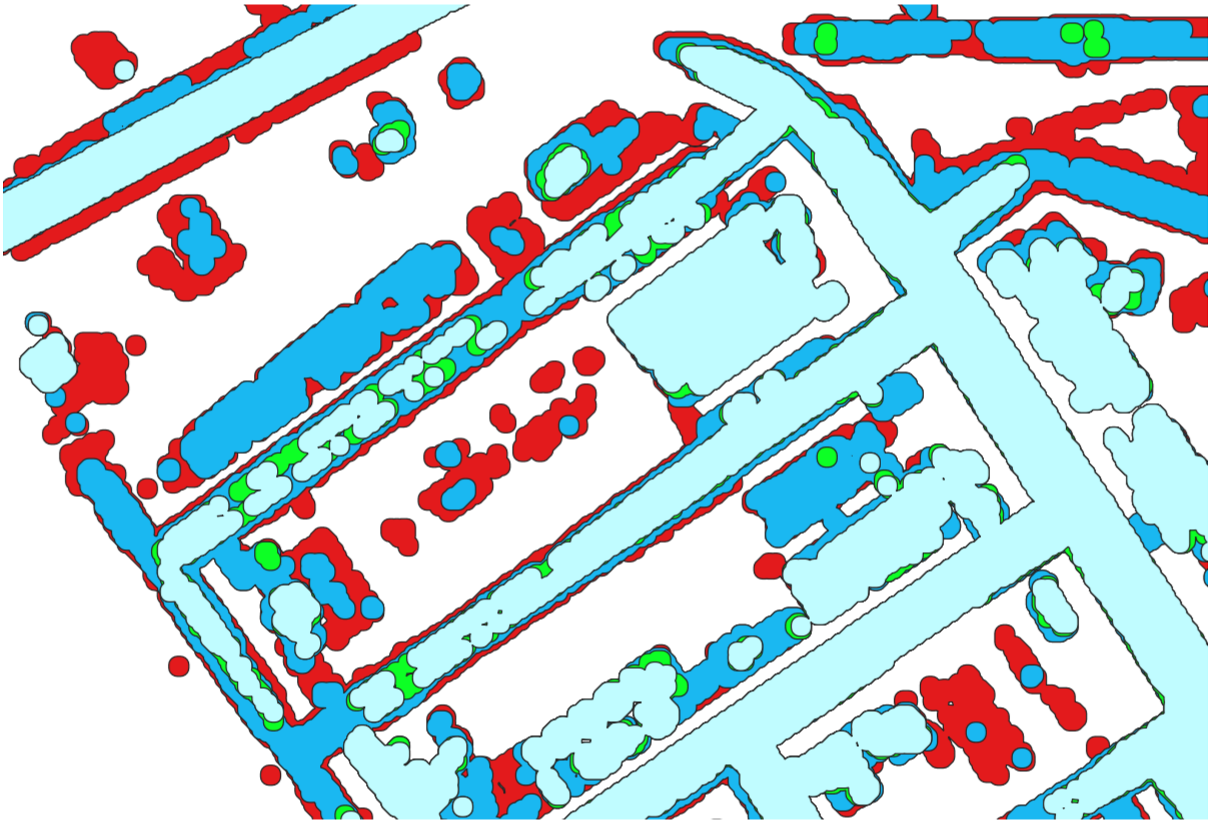

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This thesis is the final research project of the combined master programme Construction Management & Engineering, and Architecture, Building and Planning track Urban Systems and Real estate. Defence of the thesis takes place on the 17th of May 2021, after which the research becomes public. The Master's thesis has been carried out in accordance with the rules of the TU/e Code of Scientific Integrity.

Cover page image: 'Inundation polygons' of a rainfall of 18.9mm, 35.7mm, 50mm and 70mm in the S*tationsbuurt* in The Hague.

Acknowledgement

Conducting a research project on my own for a full year was something I knew would be challenging. Starting the project in the first weeks of lockdown and working from home most of the year for sure did not make the job easier. However, looking back, I can say I have enjoyed most of the steps of this research and I delivered a project I am proud of.

I would like to thank the municipality of The Hague for the support I received while setting up my case study. Access to the 3Di model and the city panel made the study much more relevant and innovative. Furthermore I would like to thank Stef van Dam for advising me in setting up the questionnaire, not losing patience when I came up with another crazy idea but helping me to form this into a workable survey format.

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With this research my time as a student is finished. I look back on a beautiful time in Eindhoven, and look forward to continuing to work in the field of critical infrastructure resilience in Delft.

Anoek de Jonge, May 12th 2021.

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Summary

This study presents a new perspective on the resilience assessment of critical infrastructures by proposing a framework which includes the desired level of resilience. Including the users' perspective in this resilience assessment is essential, and a method how to do this is provided. The method is applied in a case study in an urban environment and successfully demonstrates that including the users' perspective is a viable strategy, offering promising insights to researchers and policy makers.

The resilience of critical infrastructures has been put under increased pressure in recent decades by both urbanisation and climate change. To answer the question how this resilience can be secured now and in the future, first more fundamental questions were needed to be answered. What is resilient, and what is resilient *enough*? The framework proposed in this study, presented in figure 1, introduces the *desired level of resilience*. This is a standard or norm against which the *current level of resilience* should be assessed using predefined criteria.

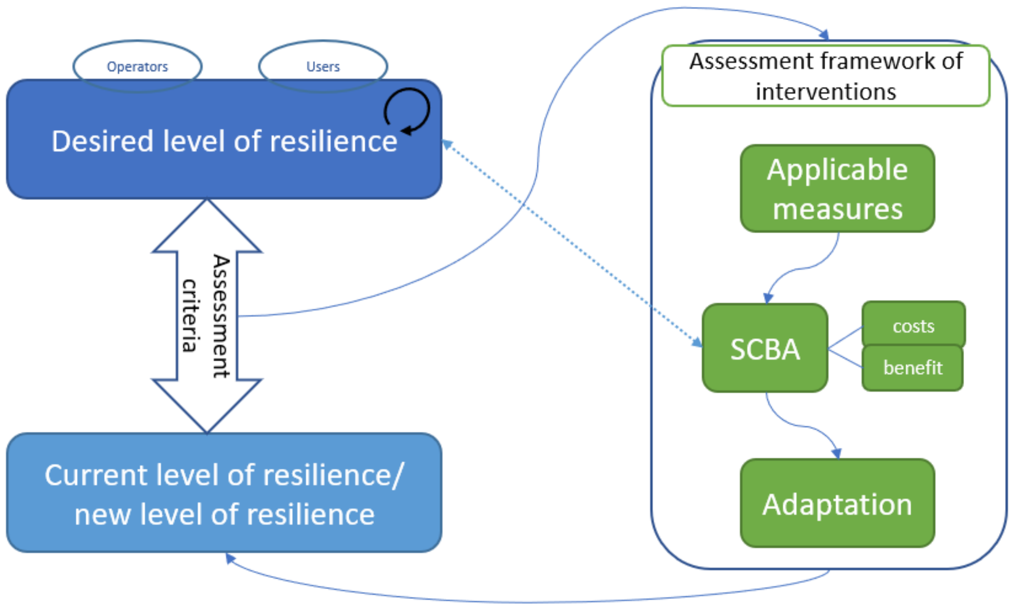


Figure 1[copied from page 20]: Framework for improving resilience by taking into account the desired level (Bles et al., 2020)

This research offers a method to quantify this *current level of resilience*, and proposes the right assessment criteria to include the users' perspective. The resilience assessment thus includes the users' resilience as well. The method is tested in a case study in the Hague, The Netherlands.

The proposed method consists of three steps to include the users' tolerance levels to critical infrastructure disruption in the resilience assessment.

1. The first step is the resilience assessment, which aims to quantify resilience in terms of *number of people affected by the disruption.* This involves a simulation of different rainfalls in a 3Di hydrodynamic model, which produces inundation maps. These maps

are then analysed in QGIS by comparing them with spatial data of the critical infrastructure systems and a population density map in the study area.

2. The second step analyses the users' acceptance levels to disruption, which can also be considered as the resilience of the users. This is quantified in the *share of people who do not accept a posed disruption.* This is done in a questionnaire-based approach using ordinal regression to analyse the data.
3. The last step combines the outcomes of the previous steps and establishes the *number of people unwilling to accept disruption.* Dimensions included in this assessment are 1) severity of hazards; 2) recurrence time of hazards; 3) types of critical infrastructures network; 4) number of people affected over time and 5) acceptance levels to disruption over time.

Part I Resilience assessment

Within the case study area, five critical infrastructure networks were assessed: the road network, the electricity network, the mobile network and the accessibility of the hospital HMC Westeinde and supermarkets. The former two networks are included in the quantification of resilience.

The number of people affected by the disruption of the network is calculated for different rainfall events with different predicted recurrence times. The results are presented in resilience triangles, which show the disruption over time. The calculations show that the number of people affected by electricity outage is estimated to be relatively low compared to the number of people affected by road network disruption. For a rainfall of 18.9mm in one hour, which has a recurrence time of two years, 808 and 18,330 people are affected respectively (0.46% and 10.40% respectively). A rainfall of 35.7 mm in one hour, predicted to happen once every ten years, leads to 1733 people (0.98%) affected by electricity outage and 41,330 people (23.44%) affected by road network disruption.

The mobile network will not be affected by the rainfalls. Furthermore it is unlikely that the area around the hospital HMC Westeinde will be flooded, nor will the electricity fail. However, the accessibility of the hospital will be reduced due to the flooding of important access roads. The accessibility of supermarkets is not significantly affected by flooding either. Only a limited number of the grocery stores is predicted to close due to flooding or electricity outage. These are all located in areas with a redundant number of other supermarkets.

Part II Acceptance levels to disruption

An analysis of the questionnaires show that the acceptance of disruption is relatively high. Users were asked to evaluate the trade-off between accepting the disruption or moving somewhere else due to unacceptable levels of disruption. Disruption of the electricity network was found to have the strongest influence on acceptance levels. Some socio-demographic characteristics were included. Findings showed that lower education levels are related to lower acceptance levels to disruption. Furthermore, younger people tend to accept the disruption of critical infrastructures less than older people.

Part III Including the users' tolerance levels in the resilience assessment

The combined results of the resilience assessment with the acceptance levels are visualised in acceptance triangles. The maximum number of people who do not accept the disruption after a certain duration is used to define the number of people unwilling to accept disruption of a particular network. For both networks, the 35.7mm rainfall event turned out to cause the highest level of unaccepted disruption. Electricity disruption would lead to a maximum of 25 people (0.014%) regarding the disruption as unacceptable. Road network disruption would lead to 1,243 people (0.70%) unwilling to accept the disruption. Scenarios with different socio-demographic characteristics of the population and increasing recurrence times are presented as well.

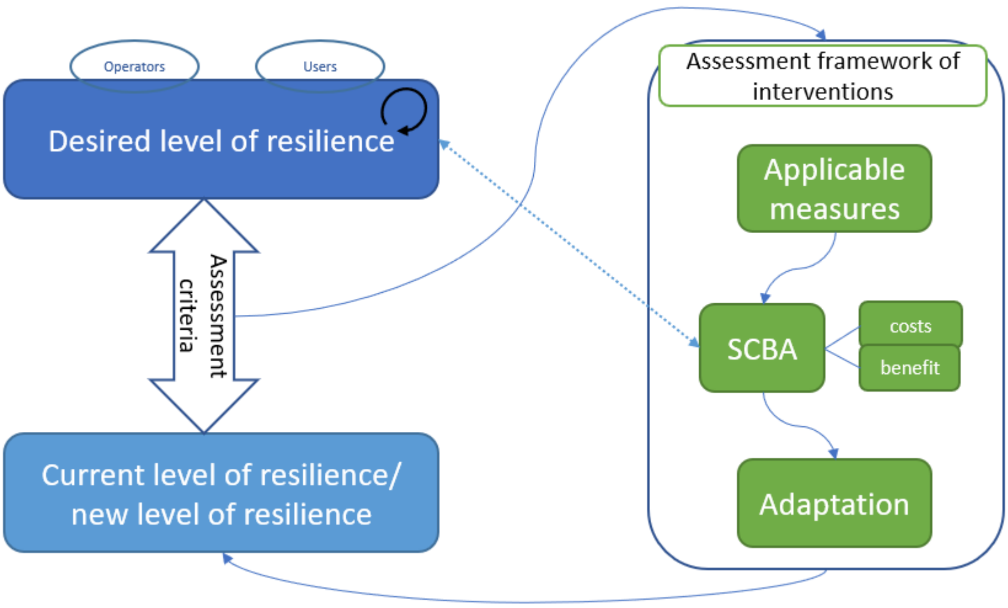
If one could conclude that the current level of risk and resilience in the study area is generally accepted, these percentages could serve as an input to what the order of magnitude could be for the *desired level of resilience*. However, according to the proposed framework, determining the desired level or resilience also entails an evaluation of costs of measures as well as other factors. Furthermore, deciding what is acceptable and what is not, is a political question to which research can only give input but no final answers.

This method demonstrates that the number of people who refuse to accept the disruption can be lowered by either increasing resilience of the critical infrastructures, or increasing the resilience of the infrastructure users. The former approach leads to measures related to flood mitigation, such as increasing infiltration or increasing robustness and redundancy of the networks. The latter strategy would aim to increase acceptance levels to disruption. One way of achieving this is preparing inhabitants of an area prone to flooding for the possible consequences.

Nederlandse samenvatting

Deze studie presenteert een nieuw perspectief op de beoordeling van de veerkracht van vitaal en kwetsbare infrastructuren door een raamwerk voor te stellen dat het gewenste niveau van veerkracht meeneemt. Het gebruikersperspectief in deze veerkrachtbeoordeling is essentieel, en er wordt een methode aangereikt om dit te doen. De methode wordt toegepast in een casestudy in een stedelijke omgeving en toont met succes aan dat het opnemen van het gebruikersperspectief een haalbare strategie is die veelbelovende inzichten biedt aan onderzoekers en beleidsmakers.

De veerkracht van vitale infrastructuren is de afgelopen decennia onder toenemende druk komen te staan door zowel verstedelijking als klimaatverandering. Om de vraag te beantwoorden hoe deze veerkracht nu en in de toekomst kan worden gewaarborgd, moesten eerst meer fundamentele vragen worden beantwoord. Wat is veerkrachtig, en wat is veerkrachtig *genoeg*? Het procesraamwerk dat in deze studie wordt voorgesteld, weergegeven in figuur 1, introduceert het *gewenste niveau van veerkracht* (*desired level of resilience*). Dit is een standaard of norm waartegen het *huidige niveau van veerkracht* (*current level of resilience*) moet worden beoordeeld aan de hand van vooraf gedefinieerde criteria.



Figuur 1[gekopiërd van pagina 20]: procesraamwerk voor het verbeteren van de veerkracht van vitaal en kwetsbare infrastructuur systemen, rekening houdend met het gewenste niveau van veerkracht (*desired level of resilience)* (Bles et al., 2020).

Dit onderzoek biedt een methode om dit *huidige niveau van veerkracht* te kwantificeren en stelt de juiste beoordelingscriteria voor om het gebruikersperspectief mee te nemen. De beoordeling van de veerkracht omvat dus ook de veerkracht van de gebruikers. De methode is getest in een casestudy in Den Haag (Nederland). De voorgestelde methode bestaat uit drie stappen:

1. De eerste stap is een uitgebreide stresstest, die tot doel heeft de veerkracht te kwantificeren in termen van het *aantal mensen dat door de verstoring wordt getroffen.* Dit is gedaan door verschillende buien te simuleren in een 3Di

hydrodynamisch model, wat resulteert in overstromingskaarten. Deze kaarten zijn vervolgens geanalyseerd in QGIS door ze te vergelijken met ruimtelijke gegevens van de kritieke infrastructuursystemen en de bevolkingsdichtheid.

2. De tweede stap analyseert de acceptatieniveaus van gebruikers voor verstoring. Deze stap kan ook gezien worden als de veerkracht van de gebruikers, die wordt gekwantificeerd in *percentage van de mensen die een gestelde verstoring niet zal accepteren.* Door middel van een vragenlijst aan gebruikers met verschillende uitval scenario's is data verkregen, welke zijn geanalyseerd met behulp van ordinale regressie.
3. De laatste stap combineert de uitkomsten van de voorgaande stappen en stelt het *aantal mensen dat een verstoring niet accepteert* vast. De dimensies die in deze beoordeling zijn opgenomen zijn: 1) Hevigheid van de bui; 2) Herhalingstijd van de bui; 3) Type vitaal en kwetsbaar infrastructuurnetwerk; 4) Aantal mensen dat is getroffen door uitval van de netwerken op verschillende tijdspunten; 5) Acceptatieniveaus voor verstoring op verschillende tijdspunten.

Deel I Uitgebreide stresstest

Binnen het casusgebied zijn vijf vitale infrastructuurnetwerken beoordeeld: het wegennet, het elektriciteitsnet, het mobile netwerk en de bereikbaarheid van supermarkten en het ziekenhuis HMC Westeinde. Voor de eerste twee netwerken is daadwerkelijk een kwantificering van veerkracht gemaakt. De resultaten worden gepresenteerd in veerkrachtdriehoeken, die de verstoring in de tijd laten zien. Het aantal mensen dat wordt getroffen door een stroomstoring, zal naar verwachting relatief laag zijn in vergelijking met het aantal mensen dat wordt getroffen door een storing in het wegennet. Voor een regenval van 18,9 mm in één uur, met een herhalingstijd van twee jaar, zijn dat respectievelijk 808 en 18.330 mensen (respectievelijk 0,46% en 10,40%). Een regenval van 35,7 mm in één uur, die naar verwachting eens in de tien jaar zal gebeuren, leidt ertoe dat 1733 mensen (0,98%) worden getroffen door een stroomstoring en 41.330 mensen (23,44%) worden getroffen door een verstoring van het wegennet. Het mobile netwerk zal niet worden verstoord door hevige neerslag. Ook is het niet aannemelijk dat het gebied rond het ziekenhuis HMC Westeinde onder water komt te staan, noch dat de elektriciteit daar uitvalt. Door de overstroming van belangrijke toegangswegen zal de bereikbaarheid van het ziekenhuis echter afnemen. De bereikbaarheid van supermarkten wordt niet significant beïnvloed door wateroverlast. Verwacht wordt dat slechts een beperkt aantal supermarkten zal sluiten vanwege overstromingen of stroomuitval. Deze bevinden zich allemaal in gebieden met voldoende andere supermarkten.

Deel II Acceptatieniveaus voor verstoring

Over het algemeen bleek dat de acceptatie van verstoring relatief hoog is. De gebruikers werd gevraagd om de afweging te evalueren tussen het accepteren van de verstoring of verhuizen naar een andere locatie vanwege onaanvaardbare niveaus van verstoring. Verstoring van het elektriciteitsnet bleek de hoogste invloed te hebben op het acceptatieniveau. Uit de bevindingen bleek ook dat lagere opleidingsniveaus verband houden met lagere acceptatieniveaus van verstoring. Ook accepteren jongere mensen de verstoring van kritieke infrastructuren minder dan ouderen.

Deel III Opnemen van de tolerantieniveaus van de gebruikers in de veerkrachtbeoordeling

De gecombineerde resultaten van de uitgebreide stresstest met de acceptatieniveaus zijn gevisualiseerd in acceptatiedriehoeken. Het maximale aantal mensen dat de storing na een bepaalde tijd niet accepteert, wordt gebruikt om het aantal mensen te definiëren dat de storing van een bepaald netwerk niet accepteert. Voor beide netwerken bleek de regenval van 35,7 mm tot de grootste niet-geaccepteerde verstoring te leiden. Stroomstoring zou ertoe leiden dat maximaal 25 mensen (0,014%) de storing niet accepteren. Wegennet verstoring zou leiden tot 1.243 (0,70%) de mensen niet de verstoring aanvaarden. Scenario's met verschillende sociaal-demografische kenmerken van de bevolking en toenemende herhalingstijden worden ook gepresenteerd.

Als men zou kunnen concluderen dat in de huidige situatie in het studiegebied het niveau van veerkracht wordt geaccepteerd, zouden deze percentages kunnen dienen als input voor wat de orde van grootte zou kunnen zijn voor het *gewenste niveau van veerkracht.* Volgens het voorgestelde kader brengt het bepalen van het gewenste niveau echter ook een evaluatie van de kosten van maatregelen met zich mee. Dit onderzoek moet daarom worden gezien als een indicatie van hoe het gewenste niveau kan worden vastgesteld. Het is een politiek debat om vast te stellen wat acceptabel is en wat niet, waarop onderzoek alleen maar input kan leveren.

Deze methode toont aan dat het aantal mensen dat de verstoring niet accepteert, kan worden verlaagd door ofwel de veerkracht van de kritieke infrastructuren te vergroten, ofwel de veerkracht van de gebruikers van de infrastructuur te vergroten. De eerste benadering leidt tot maatregelen die verband houden met het beperken van overstromingen, bijvoorbeeld het vergroten van de infiltratie of het vergroten van de robuustheid en redundantie van de netwerken. Het vergroten van de weerbaarheid van de gebruikers kan bijvoorbeeld worden behaald door inwoners van een overstromingsgevoelig gebied voor te bereiden op mogelijke gevolgen.

Abstract

This study presents a new perspective on the resilience assessment of critical infrastructures by proposing a framework which includes the desired level of resilience. Including the users' perspective in this resilience assessment is essential, and a method how to do this is provided. The method is applied in a case study in an urban environment and successfully demonstrates that including the users' perspective is a viable strategy, offering promising insights to researchers and policy makers.

The proposed method consists of three steps to include the users' tolerance levels in the resilience assessment. The first step is the resilience assessment, which aims to quantify resilience in terms of *number of people affected by the disruption.* This is done by simulating different rainfalls in a 3Di hydrodynamic model and spatially comparing them with critical infrastructure and population data. The second step analyses the users' acceptance levels to disruption, which can be seen as the resilience of the users and is quantified in the *share of people who do not accept posed disruption.* A questionnaire-based approach is carried out using ordinal regression to analyse the data. The last step combines the outcomes of the previous steps and establishes the *number of people unwilling to accept disruption.* Dimensions included in this assessment are 1) Severity of the hazard; 2) Recurrence time of the hazard; 3) Type of infrastructure network; 4) Number of people affected over time; 5) Acceptance levels to disruption over time.

Findings of the study indicate that within the study area the risks of not accepted disruption is relatively low. The research gives input to what a norm could be for a *desired level of resilience.* Furthermore it demonstrates that in proposing measures to improve resilience of networks, the resilience of the user should not be overlooked.

Keywords: critical infrastructure, resilience, user tolerance

Glossary

Acceptance triangles

Visualization of the current level of resilience which includes the users' acceptance levels to disruption of critical infrastructures, as well as the disruption of the network due to a certain hazard. Acceptance triangles combine the resilience triangles of the infrastructures and acceptance levels of users to disruption.

Critical infrastructure

Those infrastructures that serve a vital service to society. For example the road or electricity network.

Current level of resilience

Part of the proposed framework in this research which relates to the resilience of the critical infrastructure system at the present moment. The level of resilience should be quantified using predefined indicators. This research proposes to do this by assessing the infrastructure, as well as the resilience of the user.

Desired level of resilience

Part of the proposed framework in this research which is the ambition level to the amount of resilience a system of critical infrastructures needs. This can be a norm or standard and should be quantified. This research argues to include the users perspective into norm setting.

Recurrence time

The expected frequency a hazard will occur, measured in years. The term is sometimes abbreviated as RT.

Resilience

As adopted from the IMPROVER project: *"The ability of a critical infrastructure system exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, for the preservation and restoration of essential societal services* (L. Petersen, Lange, and Theocharidou 2020, p1.)*".*

Resilience assessment

The process of establishing the current level of resilience. In this research the resilience assessment includes the resilience of the infrastructure assets as well as the resilience of the infrastructure users.

Resilience triangles

A method to visualize the quantified resilience of a system over time, which makes the four temporal phases of resilience clear: resist, absorb, accommodate to and recover from.

Risk

A function of the probability that a certain hazard will occur, the exposure of people or objects to this hazard, and the vulnerability of these people or objects to the hazard.

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1. Introduction

1.1 Problem definition

The latest report of the International Panel on Climate Change again established that human activities have likely caused the world's temperature to rise approximately 1°C compared to pre-industrial levels. Furthermore, the predictions are that between 2030 and 2052 the climate will have heated up an additional 0.5°C (IPCC, 2018). The increasing temperature leads to a changing global climate, which results in weather becoming more extreme and so called extreme weather events will occur more often (IPCC, 2012). In the Netherlands, four specific threats arising due to climate change have been identified in the Delta Program Spatial Adaptation: floods, heavy rains, extreme heat and drought. The likelihood and intensity of these threats are predicted to increase into the future (Delta Programma Ruimtelijke Adaptatie, 2016). Cities, in particular, are vulnerable to these threats due to the high concentration of people. Moreover, due to the low permeability of surfaces cities are more prone to flooding (Pregnolato et al., 2017). Also, the increasing population density of cities due to urbanization puts more and more pressure on the infrastructure networks. Critical infrastructure networks are those that serve a vital or critical function to society. For example: the electricity or water network. If these are disrupted due to any cause, this has major consequences for a city and its inhabitants.

When society is exposed to a hazard this leads to a certain risk. Risk can be defined in many ways. Often risk is described as a function of three elements: *hazard, vulnerability,* and *exposure.* The first element *hazard* refers to the probability that a hazardous event with a certain intensity will take place. Hazardous events with high intensity often have a low probability of occurrence. In general, the lower the likelihood, the higher the intensity of a hazard will be. *Exposure* refers to the objects and people in the area on which a hazard can have an impact. If a hazard occurs in a densely populated area, this imposes higher risks than when it occurs in an uninhabited area. Due to socio-economic changes, people live in denser area than they used to and therefore there are more people reliant on critical infrastructures. This increases the exposure of people. Lastly, the term *vulnerability* refers to the capacity of the exposed elements to react and deal with the hazard. It is related to the fragility or robustness of the area where the hazard takes place (IPCC, 2012).

Concluding, the combination of increasing urbanization and climate change puts more pressure on critical infrastructures in the cities and increases the risk of disruption. Hence it is important to protect the networks which serve vital functions in the cities. This is the domain of critical infrastructure resilience.

In the Netherlands, a roadmap is developed to protect critical infrastructures from disruption of hazards (Bles et al., 2020). In six steps an analysis is made from identifying impacts of hazards to proposing measures to improve the resilience of the networks. These steps are the following:

1) Carry out a stress test to identify which critical infrastructure networks are vulnerable
2) Analyse the impact if such a network is disrupted
3) Identify possible cascading effects

4) Determine most important risks
5) Set the ambition level
6) Select resilience improving measures

In the first four steps data is gathered on the specific locations, hazards and critical infrastructures. The current level of resilience is established. The fifth step sets the ambition of how resilient a system should be. With this, the right measures can be selected in the last step. This approach seems rather straightforward. However, the whole process of the theoretical roadmap has never been carried out in practice and much remains unclear how to carry out the steps exactly. Most municipalities are still in the early phases of conducting stress tests to map the consequences of hazards. Hence, research on this subject and these phases is necessary.

Also, in academics, the call for more research on improving infrastructure resilience is present. Previous research has focused mainly on identifying risks, quantifying the resilience of critical infrastructures, and proposing measures. However, no consensus exists yet on what approach should be taken. Moreover, a proven methodology how to establish a certain ambition level to the amount of resilience needed does not exist.

1.2 Research aim

The framework presented in figure 1 visualizes how desired resilience levels can be included in improving the resilience of critical infrastructure.

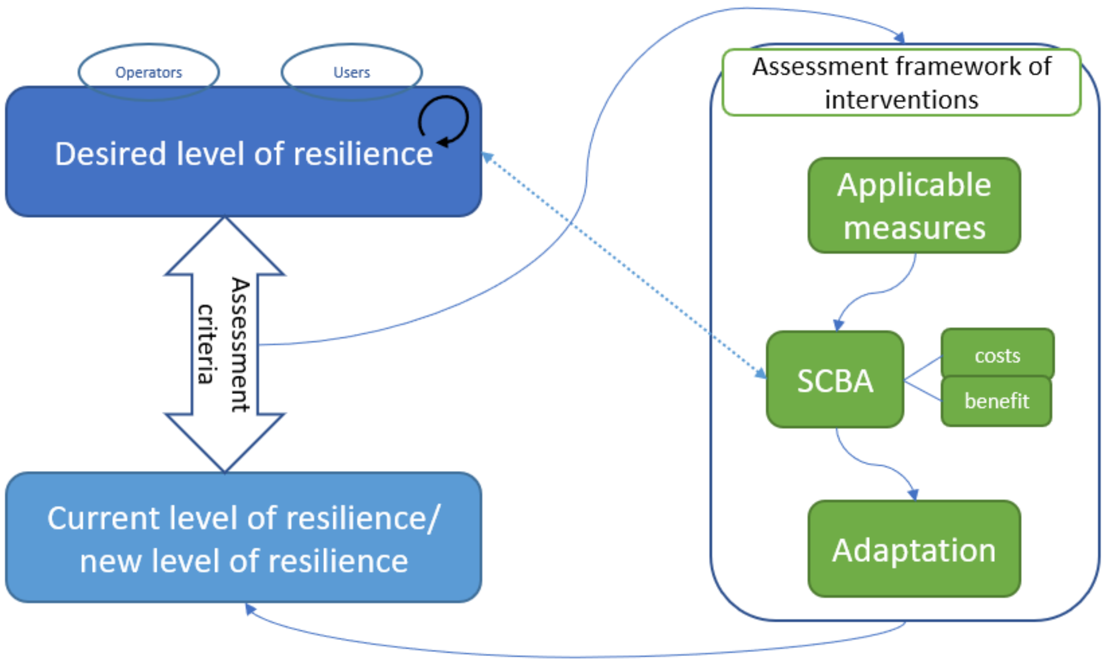

Figure 1: Framework for improving resilience by taking into account the desired level (Bles et al., 2020).

The blue part of the framework indicates that there should be a comparison between the *desired level of resilience* and the *current level of resilience*. These two need to be compared using the same indicators to evaluate if an increase in resilience of the system is necessary. The green part of the framework shows that during the evaluation of measures in a social cost-benefit analysis (SCBA), predicted costs could lead to lowering the ambitions to the *desired level of resilience*. Hence, after choosing certain measures, the new level of resilience of the system should be evaluated in order to check if it complies with the desired level.

This framework presents the basis of this research and aims at answering the overarching question: *How to attain a resilient system of critical infrastructures?*

However, to answer this question other questions need to be answered first. What is a resilient system, and when is it resilient *enough?* Insight is required in how this desired level of resilience can be established and what metric is necessary. Previous research suggests that the infrastructure user should be included in determining this ambition (Petersen, Lundin, et al., 2020). To follow up on that, the aim of this research is to **propose a method that includes the users' perspective in the resilience assessment.** This will give input to what kind of norm is required to set the desired level of resilience.

This method focuses on establishing an indicator to determine the current level of resilience which combines the technical resilience of the system and the acceptance levels of users to the system's disruption.

1.3 Research design and research questions

The method is demonstrated in a case study. The main research question of the case study is: *How can users' acceptance levels to critical infrastructure disruption be included in the resilience assessment?*

Three sub-questions can be formulated for this case study:

1) How can resilience of critical infrastructures be defined and quantified?
2) How can the users' acceptance levels to disruption of critical infrastructures be defined and quantified?
3) How can quantification of resilience of critical infrastructures be combined with the users' acceptance levels to disruption? Can this give input to a desired level of resilience?

These three research questions align with chapters 4, 5 and 6, (respectively case study Part I, II and III). In order to carry out the case study appropriately, first a literature study is done to gain background information. With lessons from this literature review, the case study is set up.

1.4 Reading guide

The research starts with a literature review covering the basic concepts in the field of critical infrastructure resilience. It will attempt to gain background information concerning the state of the art of critical infrastructure resilience and its related concepts. The next four chapters will present the case study which will demonstrate the methodology proposed in this research. First, the case study and methodology will be introduced. Case study part I and part II (respectively chapter 4 and 5) are research projects on their own. They each have their own methodology. Chapter 6 combines the results of the two previous chapters and demonstrates the new approach to including users' acceptance levels in resilience quantification. It also shows how the proposed method could give input in defining the desired level of resilience.

In chapter 7 the main conclusions of this research are presented, followed by future research directions.

2. Literature review

2.1 Introduction

This chapter aims to provide background to the domain of critical infrastructure resilience and its' terminology as well as to give input to the case study presented further on in the research. Academic literature along with project reports are used as sources in this literature research. Five research questions are answered in each sub section of this chapter ending with a short conclusion. The research questions are:

1) What is a resilient network of critical infrastructures?
2) What methods can be used to quantify resilience?
3) Do standards exist to describe the desired level of resilience?
4) How can the infrastructure user be included in establishing a desired level of resilience?
5) How can resilience improving measures appropriately be selected?

2.2 What is a resilient network of critical infrastructures?

Often *resilience* is regarded as a buzzword, rather than a property of an infrastructure system (Linkov et al., 2014). Though it is not an easy word to understand, and a variety of definitions in different fields exist. First definitions of *resilience* and *critical infrastructure* are provided. Thereafter, in order to understand the full meaning of the word *resilience*, an elaborate description of the concept in relation to critical infrastructure is provided.

2.2.1 Definition resilience

Resilience can be defined in many ways across a variety of disciplines, including infrastructure resilience. The word originates from latin, *resilire,* meaning: to jump back. It was first used in the context of ecological resilience (Holling, 1973), but later on expanded to disciplines as social science, economy and engineering (Cimellaro et al., 2016). Past twenty years the amount of publications on *resilience* expanded rapidly. Though, there is still no universally accepted definition, and because the concept exists in many domains the question arises if this is even desirable. However, it is important to be able to communicate between the different fields what is meant by the concept. Hence, Koslowski & Longstaff (2015) proposed a multidisciplinary framework to classify the different definitions and provide a holistic understanding. The framework distinguishes four categories with a high or low degree of normativity and complexity. The four categories are I: The capacity to rebound and recover, II: The capacity to maintain a desirable state, III: The Capacity of a system to withstand stress, and IV: The capacity to adapt and thrive. In many definitions related to (critical) infrastructure resilience, these four components are included as well.

There are many sources summarizing the definitions of resilience, even within the field of infrastructure resilience. For example, the Critical Infrastructure Preparedness and Resilience Research Network (CIPRNet), published an extensive list of definitions used in different domains and across different countries (CIPRNet). Another source worth mentioning is the lexicon of definitions by the IMPROVER project, a European Union funded project, on which parts of this research is based Theocharidou et al. (2016). Furthermore Ayyub, (2014) presents an overview of most commonly used definitions with high impact, and in PIARC an extensive literature review is presented on definitions of resilience in the context of infrastructure and specifically roads (PIARC). To give an impression of the variety in definitions, but also similarities, some important definitions are presented below:

- With regards to climate change and adaptation:
  Definition of the International Panel on Climate Change (2007): "The ability of **a social or ecological system** to **absorb** disturbances while retaining the same basic structure and ways of functioning, the capacity of **self-organization**, and the capacity to **adapt to stress and change**" (IPCC, 2007, p. 86)

- In the urban context:
  Definition of the 100 Resilient Cities Network: "The capacity of **individuals, communities, institutions, businesses, and systems within a city** to **survive, adapt, and grow**, no matter what kinds of chronic stresses and acute shocks they experience." (Resilient Cities Network, n.d.)
  From the ISO 37123:2019 norm on sustainable cities and communities – indicators for resilient cities: "adaptive capacity of an organization in a complex and changing environment" (Sustainable cities and communities — Indicators for resilient cities | ISO 37123, 2019).

- In the context of disaster risk reduction:
  Definition of the United Nations International Strategy for Disaster Reduction (2009): "The ability of a **system, community or society** exposed to hazards to **resist, absorb, accommodate to and recover from** the effects of a hazard **in a timely and efficient manner**, including through the **preservation and restoration of its essential basic structures and functions**." (UNISDR, 2009)
  Definition of the National Academy which is widely used: "The ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse event." (National Research Council, 2012, p.1)

In this research the definition of *resilience,* which is used by the IMPROVER project is selected. It has many similarities with the definition from the UNISDR, but is specified to the critical infrastructure context. In this project emphasis lies on the shift from protecting assets to being able to provide a continuous service level. Furthermore, the views of infrastructure operators were included as well. This reflects the themes of this research and hence this definition is chosen. It reads:

"The ability of a critical infrastructure system exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, for the preservation and restoration of essential societal services (L. Petersen, Lange, and Theocharidou 2020, p1.)*".*

2.2.2 Definition critical infrastructures

Critical infrastructure can be defined as "those infrastructures whose services are so vital that their disruption would result in a serious, long-lasting impact on the economy and society" (Commission of the European Communities, 2006). The International Organization for

Standardization specifies it in ISO 37123:2019 as "Physical structures, facilities, networks and other assets which provide services that are essential to the social and economic functioning of a community or society" (Sustainable cities and communities — Indicators for resilient cities | ISO 37123, 2019). In the Netherlands, critical infrastructures are classified in seven functions:

1) Energy - electricity, natural gas and oil
2) Telecom/ICT - public network and basic system for emergency communication
3) Water network - drinking water and wastewater
4) Health – hospitals
5) Surface water
6) Transportation - rail and road network
7) Chemicals and nuclear plants (Deltaprogramma Ruimtelijke Adaptatie, 2014)

These definitions all put emphasis on infrastructures as an asset which needs to be protected. In New Zealand, there is a different focus, looking more at the functions the infrastructure provides. Here critical infrastructures are referred to as *lifeline utilities* or *lifeline systems* (Petersen, Lange, et al., 2020). This tendency can also be observed in Europe in the Nordic countries. Pursiainen (2018) writes about the *Nordic model* of critical infrastructure, where he compares policies of Denmark, Finland, Norway, and Sweden to other European countries. A division is made between countries with emphasis on protecting their infrastructures, or their vital societal functions. One of his conclusions states that the other European countries have the tendency to focus on protecting the critical infrastructures, whereas Nordic countries focus on the services they provide which need to be protected. He calls for a shift in resilience thinking in this direction.

2.2.3 Call for a shift in resilience thinking

This difference is part of a shift in how to approach resilience thinking. At first the view was mainly on critical infrastructure protection (often referred to as CIP). While around 2015 the emphasis started to shift to critical infrastructure resilience (CIR). This includes the view that full protection of infrastructures can never be guaranteed, and hence should also not be strived for (Pursiainen & Gattinesi, 2014; Rød et al., 2020a). Providing full protection is not only unreasonable, but also not cost effective and therefore undesirable. Petersen et al., (2020) points at a change in resilience thinking which is twofold. On one hand, as discussed above, going from asset focused to service focused. On the other hand, acknowledging that there are events which you cannot plan for because they are too extreme. A focus towards the aspects of resilience as flexibility and adaptability is encouraged by the author. Summarizing these two movements she calls for a shift from risk to resilience, which includes moving from protecting your assets from any type of hazard, to ensure a continuous (minimum) level of essential services to the public. From this point of view it makes sense to start questioning what this minimum level of essential services should be, which will be elaborated on later in this chapter.

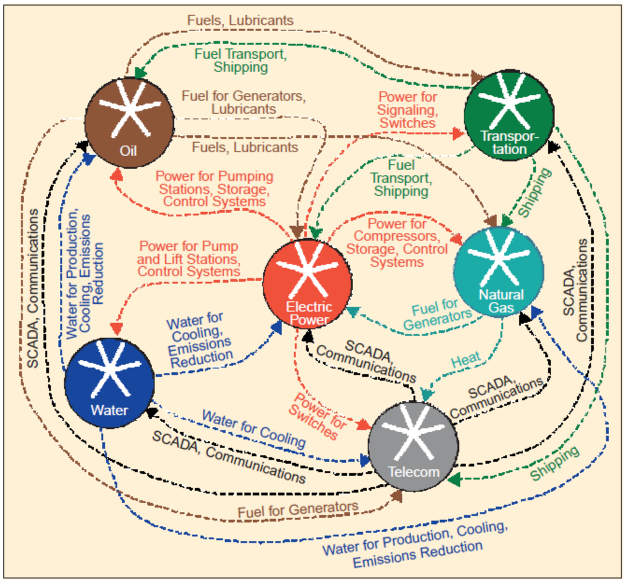

Figure 2: An example of interdependent critical infrastructure systems (Rinald et al., 2001).

2.2.4 Critical infrastructure networks and cascading effects

As infrastructure is inherently part of a network of infrastructures which are interdependent on each other, it is always necessary to review the resilience of critical infrastructure as part of a system and never in isolation (Pitt, 2008). A schematic representation of an example of such a system is shown in figure 2.

An infrastructure system is thus always dependent on other infrastructure systems. Infrastructure dependency is defined by Rinaldi et al. (2001) as '*a unidirectional relationship between infrastructures, where the state of one infrastructure influences or correlates with the state of the other*'. They also mention four types of dependencies: 1) Physical, 2) Cyber, 3) Logical and 4) Geographical. Furthermore, he adds that infrastructure systems should be regarded as Complex Adaptive Systems, where the complexity arises beyond the sum of the parts of the system.

Due to the complex interdependencies, a hazard event can cause multiple disruptions down the line, also referred to as cascading effects (Zimmerman & Restrepo, 2009). To give an example: When an electricity network is disrupted this may lead to malfunctioning of water sanitation plants. Also, some water pumps could get disrupted leading to flooding of roads, which reduces functionality of the road network. Because of these cascading effects it is complex to predict what risks critical infrastructure face and how to reduce the risk most effectively.

According to Johansson et al. (2015), cascading effects can be defined as such when the impacts of an initiating event adheres to the following:

1) System dependencies lead to impact propagating to other networks or systems
2) The combined impacts of the propagated event are of greater consequences than the root impacts
3) Multiple stakeholders and/or responders are involved.

However, the validity of the second argument can be questioned. In some cases, a hazard has initially more impact than the consequences due to cascading effects.

Figure 3 shows a conceptual model of how cascading effects spread after the initiating event (for example a natural hazard like a heavy storm). The initiating event has a direct impact on the so-called ‘originating systems’. These are critical infrastructure systems which will get disrupted. If these systems affect another system through a dependency it is called a first order cascading effect. The system affected by the originating system is called the dependent system. When the disruption continues onto a third system through the dependent system, it will lead to second order cascading effects (Johansson et al., 2015).

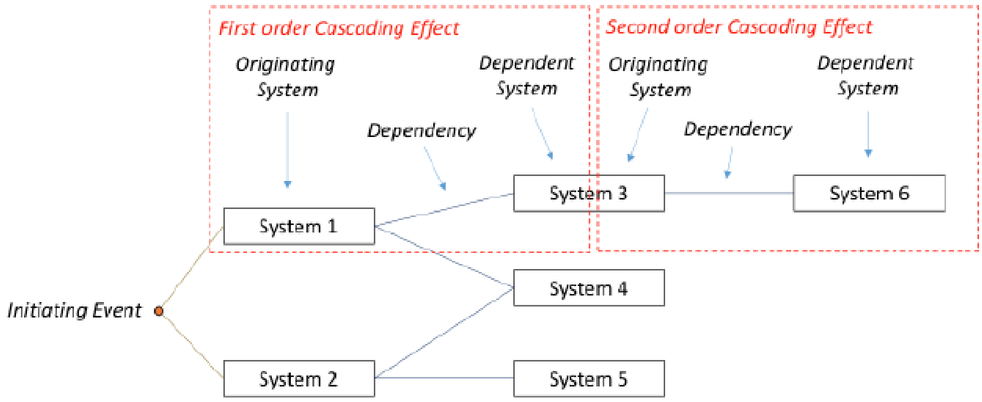

Figure 3: conceptual model of the cascading effects through different systems (Johansson et al., 2015).

Linking this to figure 1, it shows how one induced hazard can have impact on society in multiple ways through the disruption of multiple critical infrastructure systems. Because of the risks of cascading effects, it is important to look at the systems of critical infrastructures as a whole. Nevertheless this is not yet done enough (Tsavdaroglou et al., 2018). (Utne et al., 2011) add to this that often the operators and owners of critical infrastructure are aware of the risks to their own systems. However, because of the lack of knowledge about the other systems on which their system is dependent, the network remains vulnerable.

A case study in the Netherlands shows the different types of sectors which are often hit by external hazards, and to which other sectors the effects often cascade. It is shown that transport and energy systems are often disrupted by external causes and that these industries have multiple other industries which can be affected by this failure (Vogel, R., Luiijf, E., Maas, N., Dijkema, G., & Zielstra, 2014). This is visualized in figure 4. Also, it is found that in Europe 60% of the disruptions leading to cascading effects start at the energy sector, and 24% is initiated by the ICT sector (Luiijf et al., 2009). It could be expected that due to the increasing dependence on ICT systems this number has gone up.

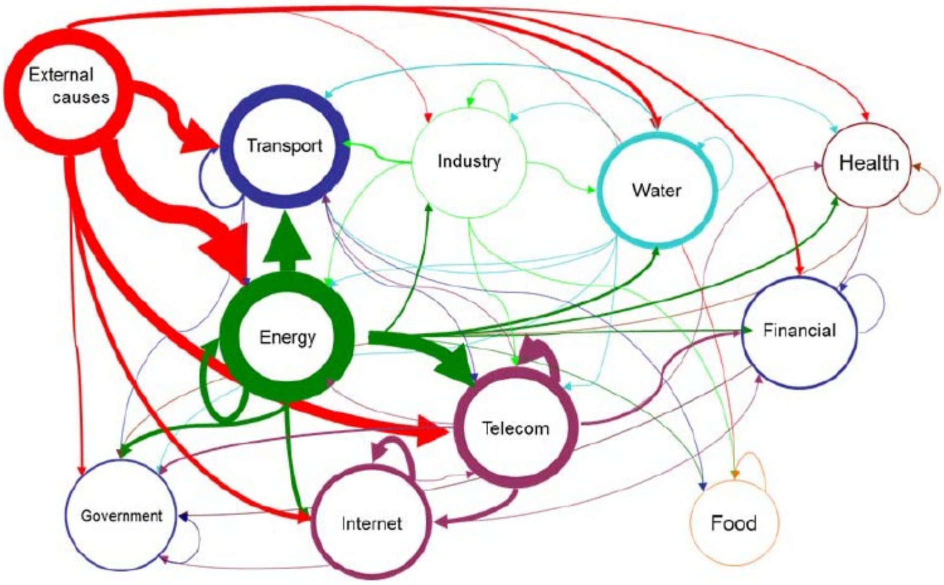

Figure 4: Relative failure of critical infrastructures in the Netherlands and its cascading effects between 2005-2011 (Vogel et al., 2014).

2.2.5 Concepts and frameworks describing critical infrastructure resilience

After establishing separate definitions of resilience and critical infrastructure, it is time to elaborate on how this can be achieved and what concepts relate to it. From the overview of definitions it can be deducted that resilience often has to do with the concepts *to prepare and plan for, absorb/resist, accommodate to recover from, and more successfully adapt to* disruptions. This classification is often used, but there are more principles to describe a resilient system. Again, there are many publications on this subject, this chapter presents a brief overview.

Often the term robustness is seen as one of the properties of a resilient system. Nevertheless Mens et al., (2011) emphasize the difference between a systems' resilience, resistance and robustness. Resistance should be thought of as the ability to withstand disturbances, whereas resilience is the ability to recover from the response to a disturbance. A systems' robustness is its ability to remain functioning under disturbances. A robust system is one where the response curve stays far from the recovery threshold for a large range of disturbance magnitudes, as presented in figure 5. From Gallopín, (2006) we can learn that robustness can also be thought of as the flip-side of vulnerability. Another way to look at the difference

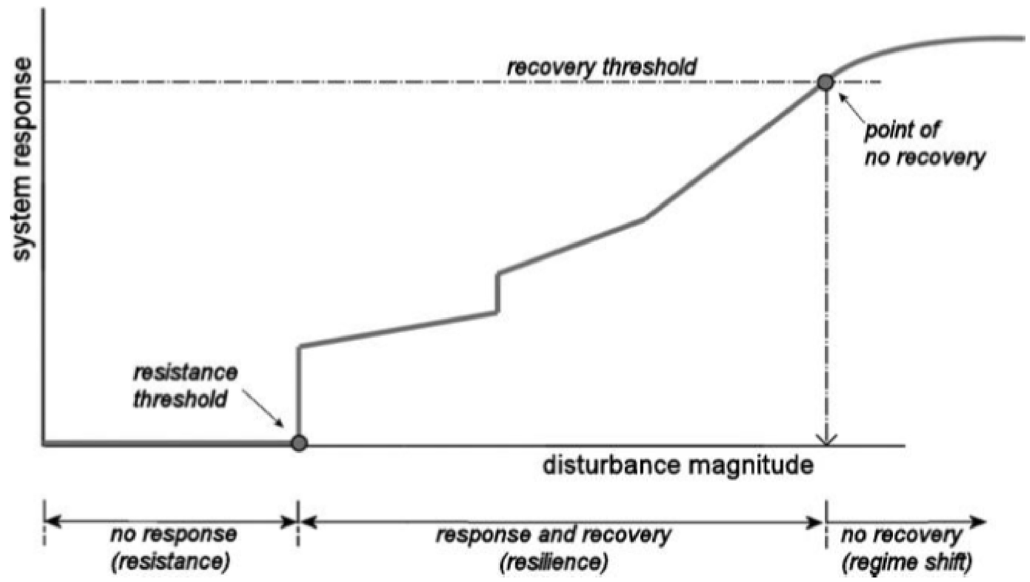

Figure 5: Theoretical response curve of a system, showing the difference between resistance and resilience and a point of no recovery (Mens et al., 2011).

between resilience and robustness, is that resilience has the capacity to non-linear adaptation and is not static, while robustness is more 'fail-safe' (Nair & Howlett, 2016; Park et al., 2012).

A commonly cited article of Woods (2015) describes four concepts included in resilience engineering. Here robustness is taken as a synonym for resilience. The other three components of resilience are: 1) as rebound from trauma and return to equilibrium (related to the original meaning of the latin word *resilire*; 2) resilience as the opposite of brittleness (relating to vulnerability it the previous section); 3) resilience as network architectures that can sustain the ability to adapt to future surprises. In a later publication of Woods' *Essentials of resilience, revised*, he adds the importance of adaptive capacity (Woods, 2019).

Another source worth mentioning is the work by Bruneau et al. (2003), who started with quantification of system resilience. According to the research, a resilient system shows the following properties:

1) Reduced failure probabilities
2) Reduced consequences from failures (can be translated to reduced lives lost, damage, negative social or economic consequences)
3) Reduced recovery time

From this summation, the four R's to resilience are defined, being *Robustness, Redundancy, Resourcefulness* and *Rapidity.* Robustness is the strength or capacity of the system to withstand any stress without losing function. Redundancy can be explained as 'the extent to which elements, systems, or other units of analysis exist that are substitutable, i.e., capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality' (Bruneau et al., 2003). Resourcefulness describes the capacity to, in case of disruption, identify the main problems and priorities and to mobilize resources. Rapidity can then be seen as the capacity to meet these priorities in time. With these four definitions, a start has been made on quantification, which is later continued by Cimellaro et al. (2010).

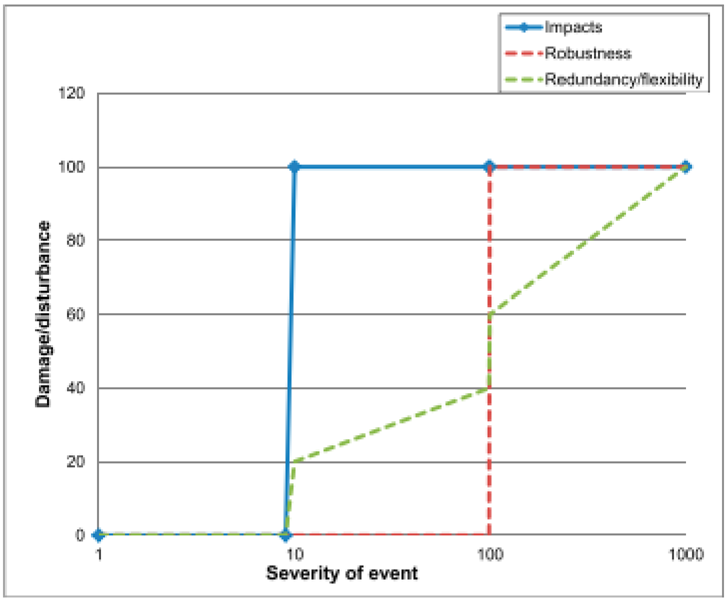

Figure 6: The relationship between the disturbance of an event with certain severity causes for a certain critical infrastructure systems.

Research by de Bruijn et al. (2019) specified on flood resilience of critical infrastructures focusses as well on the properties *redundancy* and *robustness*, and they add *flexibility.* An example of adding redundancy to a system is to have spare capacity or backups, for example in a road network, where a second road can be used to reach a certain point. Another example is in an electricity network which has a circular power supply instead of linear, so if one node fails other nodes can take over. A robust system is one which is protected against disruption, for example an elevated electricity station to prevent water to come in and cause damage during a flood. A flexible system can evolve and adapt during the disruption, for example by facilitating transportation over rail instead of roads if these are flooded.

These three concepts are nicely visualized in figure 6. The blue line represents the normal situation of a system which is exposed to a certain hazard with a certain severity, which leads to a certain amount of damage. The severity of the event is presented in logarithmic scale of the predicted recurrence time of the event. The higher the recurrence time, the higher the severity. If the system would be more *robust*, the disturbance or disruption would occur only with a more severe event. The line is shifted horizontally to the right. If the system would be more *redundant* or *flexible*, the system would be able to mitigate the disturbance once it happens, reducing the amount of disturbance per type of event. The line is thus shifted vertically.

Lastly an important framework which needs to be mentioned to assess resilience is the *City Resilience Index*, developed by Arup with support of the Rockefeller Foundation. The index describes in 52 indicators different capacities which are needed for cities to function no matter what shocks or stresses are encountered. It thus goes beyond natural hazards, but also includes economic shocks or terrorism for example. The indicators are classified in four dimensions of which *Infrastructure and Environment* is one them. The aforementioned concepts come back in indicator number 7.4 'Robust protective infrastructure' and indicator number 8.2 ‘Flexible infrastructure’. Redundancy is present in indicator number 8.3 ‘Retained spare capacity’ and number 9.1 ‘Diverse and affordable transport networks’. Furthermore, the Rockefeller foundation initiated the Resilient Cities Network which strives to connect cities and share knowledge on resilience. Seven qualities a resilient city must strive for are, apart from *redundant, robust* and *flexible*, *reflective, resourceful, inclusive* and *integrated* (The Rockefeller Foundation & ARUP, 2015).

2.2.6 Conclusion

This section presents insight in what is meant by critical infrastructure resilience. Resilience can have many definitions depending on which sector it applies but also within the critical infrastructure domain there is no consensus yet. For this research the definition offered by the IMPROVER program is chosen. Critical infrastructures can be regarded as the asset itself or the essential service it provides. In the Netherlands it still concerns seven essential assets, however a shift towards putting emphasis on the vital functions it delivers is observed. This shift also includes accepting that these vital functions cannot be protected to all hazards, but that the aim should be to be able deliver a continuous minimum level of essential services during a crisis.

Critical infrastructures are always part of other infrastructure networks and are therefore interdependent on each other. When a disruption occurs to one system, this can lead to cascading effects to other systems. In the Netherlands disruptions in the energy and ICT sector lead to the most cascading effects.

2.3 How can resilience be assessed and quantified?

2.3.1 Assessment of resilience

Resilience of critical infrastructures can be assessed in many ways using a variety of tools. The Resilience Shift is a global initiative, founded by two large engineering and consultancy firms, with the aim to build resilience within and between critical infrastructure sectors. They composed a list of 70 different tools which can be used to assess resilience, called The Resilience Toolbox (The Resilience Shift, n.d.). The user of the tool can either be a governmental organization, network operator, end user, engineer or investor. A further classification of tools is made between which types of infrastructures have the focus, which phases of a hazard are included (before or during the hazard or during the recovery phase) and if the focus is on urban or rural areas. The City Resilience Index developed by ARUP, briefly described in the previous section is adopted in this toolbox. Also, the CIrcle tool (Ciritical Infrastructures Relations and Consequences for Life and Environment) which is used to identify cascading effects, and which is used as input in the case study of this research, can be found in the toolbox.

The resilience toolbox is mainly used by practitioners. But also in academics many frameworks exist to qualitatively assess resilience. Rød et al., (2020b) present an overview of the most promising resilience assessment techniques published in the last eight years. An example is the Critical Infrastructure Resilience Index (CIRI) proposed by Pursiainen et al. (2017). The aim of the method is to holistically assess the resilience of all kinds of infrastructures exposed to all kinds of hazards. Both qualitative, semi-qualitative and quantitative metrics can be used. Figure 7 presents the overall scheme.

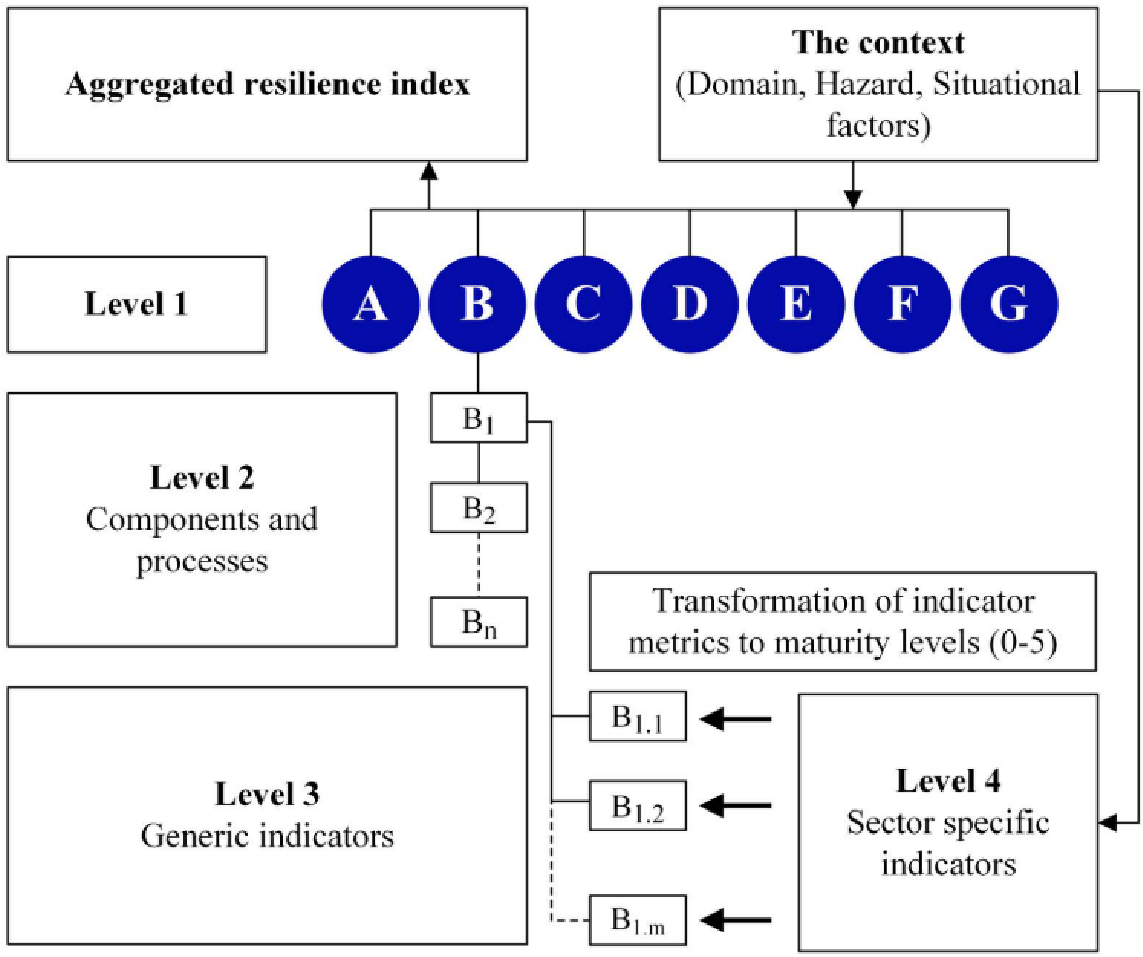

Figure 7: The Critical Infrastructure Resilience Index scheme (Pursiainen et al., 2017; Rød et al., 2020a).

The method consists of several levels. Level one differentiates the different phases of a crisis on which resilience can be assessed being *risk assessment, prevention, preparedness, warning, response, recovery* and *learning*. The phases which are found to be important to assess are to be included, this is based on expert judgement. In level 2 and 3 indicators are established and further specified. Indicators can get different weights if necessary. In level 4 the indicators are measured to arrive at a final score of resilience. The method is rather new and tested in Oslo and in Portugal. It relies heavily on formulating the right indicators and using the right metrics and weights. Though it enables comparison of systems and structures the assessment process.

2.3.2 Quantification of resilience

In general resilience is visualized in two ways, by either looking at the response of a system over time during the disaster, or by looking at the systems response for increasing severity of events. These two types are elaborated in this chapter.

The first type is visualized in figure 8. Four temporal dimensions of resilience, as deducted from the definitions of resilience *plan, absorb, recover* and *adapt* (for example the commonly used definition from the National Research Council, (2012)) are demonstrated. The temporal dimensions from the definition of critical infrastructure chosen in this research are *resist,* *absorb, accommodate to* and *recover from.* Resist would here be situated right at the point in time where the shock starts (between *plan* and *absorb)*, and *accommodate to* between *absorb* and *recover.* Critical functionality (K) here has a value between 0 and 1, but can have other metrics as well (percentage in the following example).

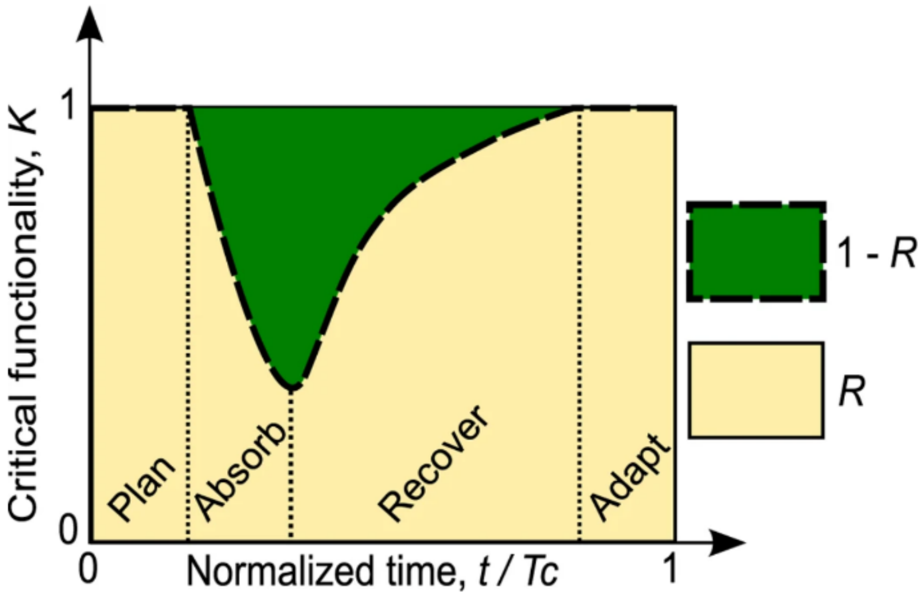

Figure 8: Critical functionality of a system over time when exposed to a certain shock and its resilience, including the concepts plan, absorb, recover and adapt (Ganin et al., 2016)

These types of graphs can also be used to quantify resilience, as shown in figure 9. Here is clear that at point A the hazardous event starts, leading to a reduced functioning of the infrastructure (in figure 9 stated as 'Q – quality of infrastructure). It drops down to a certain point B, after which the infrastructure will start to recover between t0 and t1. At point D the infrastructure functions as before. When depicting this cycle in a graph, it is called the resilience triangle (Tierney & Bruneau, 2007). This implies that a reduced probability of failure and fast recovery times after an external shock increases resilience of infrastructure systems. It allows to calculate the amount of resilience, as proposed by (Attoh-Okine et al., 2009) in the following formula:

$$Resilience = \frac{\int_{t0}^{t1} Q(t)dt}{100(t0 - t1)}$$

Q = Infrastructure quality/ performance of a system in percentages
t 0 = time of incident
t 1 = time of full recovery
According to this model, the unit of measurement of resilience are performance per unit time, where performance is measured in percentages, thus percentage over time. Lastly, (Shinozuka et al., 2003) add that in this triangle the properties of *Robustness* and *Rapidity* can be added and quantified by using the following formula:

$$Robustness = B - C$$

$$Rapidity = \frac{A - B}{t1 - t0}$$

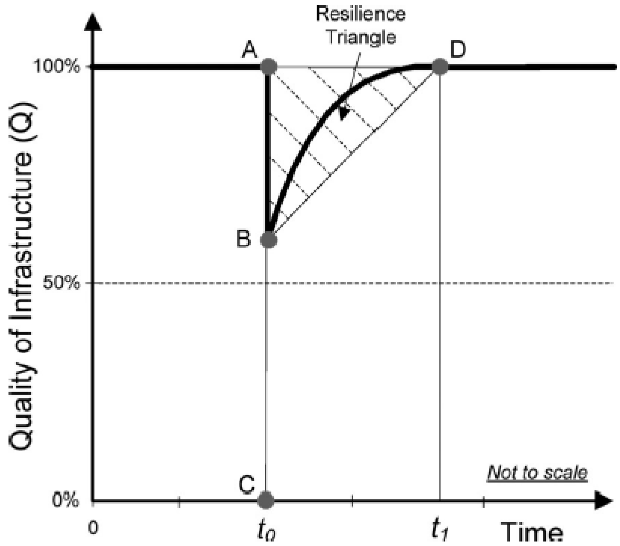

Figure 9: The resilience triangle, adopted from Tierney & Bruneau (2007).

Robustness is measured in percentages of quality of infrastructure, and rapidity in average recovery rate in percentage over unit of time. The robustness is also sometimes referred to as the maximum damage or impact of a hazard, and the rapidity as the recovery rate (Murdock et al., 2018).

The second way to quantify resilience is by including the expected recurrence time of an event in combination with the damage to or disruption of a system. Events with a high predicted likelyhood of occurrence have low severity, while events with a low predicted likelyhood have a high severity. This likelihood of occurance can be quantified in annual exceedance probablity or the inverse of this the recurrence time of an event. When drawing the curve between the expected damage of different hazards with increasing severity it is called a system response curve. The response curve is drawn per type of hazard with an increasing severity and includes only one infrastructure system. A scematic representation is given in figure 9.

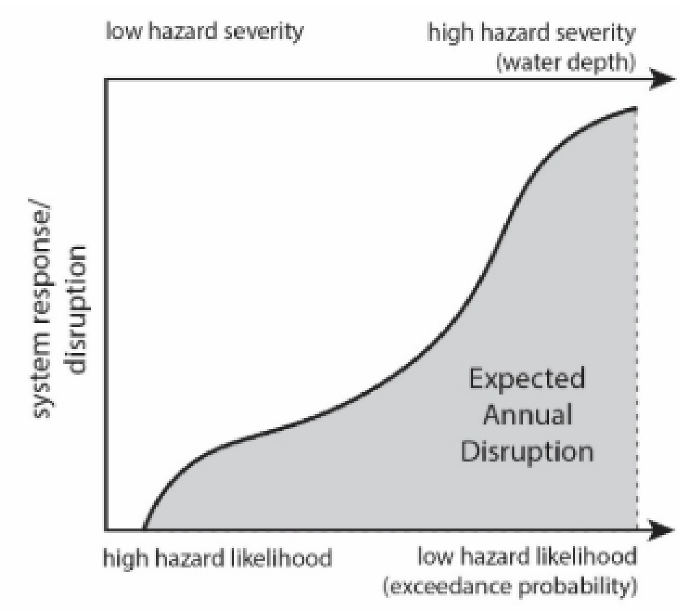

Figure 10: Relationship between likelihood of occurrence of a hazard and the amount of disruption or damage to a system (Murdock et al., 2018).

The final metric to quantify resilience using a systems response curve is by summing up the area under the curve. Depending on the metric on the y-axis, this can be either the expected annual damage (damage on the y-axis) or the expected annual disruption (as in figure 10). Damage is often quantified in terms of money. To calculate the annual expected disruption often the metric *people x disruption* time is used. *Time* can be either minutes (for example travel time loss), hours or even days. *People* is the number of people affected by the disruption. Research by Murdock et al., (2018) shows an example how this methodology is implemented in a case study in Toronto, Canada, for the road and electricity network.

The two types of quantification methods of resilience described above usually encompass one infrastructure system. In order to include multiple systems in one quantification the indirect or cascading effects should also be taken into account. An example of how this can be done is presented in the research by Tsavdaroglou et al., (2018) in a case study in Rotterdam, the Netherlands. Though, the resilience of a network is quantified as 'impact' which is dependent on several qualitative and quantitative indicators. A method to visualize resilience of networks including cascading effects is presented in this research, and it creates a start for full quantification.

A last example to quantify resilience when taking into account the recurrence time of an event is presented by Pregnolato et al., (2017). The impact of floods on the road network is quantified as a percentage of linkages disrupted, and by using network analysis transformed into additional journey time and length. This is then monetarized to enable comparison with measures to prevent flooding. Though this is a very elaborate method, it only includes the *robustness* component of a network en disregards the recovery rate of a system. It can hence only be used to assess measures which reduce the total impact, rather than including measures which speed up the recovery process.

2.3.3 Conclusion

When describing resilience of critical infrastructures often the following temporal phases are distinguished: before the event (prepare/plan for), during the event (resist / absorb/ accommodate), recovering from the event and after the event. Properties of a resilient system often found in literature are: robustness, redundancy, rapidity and flexibility. However, many more properties are described in various sources.

These properties are also often used to assess resilience. Many methods exist and still there is no consensus which method is the best. Quantification of resilience is more and more done by using a resilience triangle, which includes the temporal dimensions of resilience. Another approach to quantifying resilience is to include the exceedance probability of an event. Using that method the annual expected damage can be calculated.

2.4 Do standards exist to describe the desired level of resilience and how are they chosen?

Speaking of the desired level of resilience is a rather new term. However, when designing infrastructures the probability of failure is an important feature to include. The lower the fail probability, the more complex a design will get. This chapter sheds light on what the current practice is to set a certain standard for failure probabilities.

2.4.1 Safety design norms

The widely used principle to describe how safe something should be in safety decision making is called the ALARP technique, an abbreviation of 'As Low As Reasonably Practicable' (Jones-Lee & Aven, 2011), or sometimes ALARA meaning 'As Low As Reasonably Attainable/Achievable' (Melchers, 2001). This approach acknowledges that there are economical and practical limits to prevent unsafe situations and proposes some sort of goal or standard regarding safety. It has been used in many domains for a long time, for example in nuclear safety, water safety or off shore constructions. The method is recognized as the main approach to setting tolerance levels for acceptable risk (Health and Safety Executive (HSE), 1992; Kam et al., 1993). The ALARP principle assumes that there is an upper and lower bound between a risk which is acceptable, as shown in figure 11 (numbers purely illustrative). The upper bound is the unacceptable risk, and the lower bound is the acceptable risk but beyond the possibility to achieve. Because the lower the risk of failure, the more expensive or complex it becomes to ensure this. Hence the 'as low as possible' approach is taken, for which 'reason' and 'practicality' are leading in decision making. Furthermore, social as well as technical views on risk should be incorporated. Melchers, (2001) states the main shortcomings of this approach, but acknowledges that proposing a better technique is difficult.

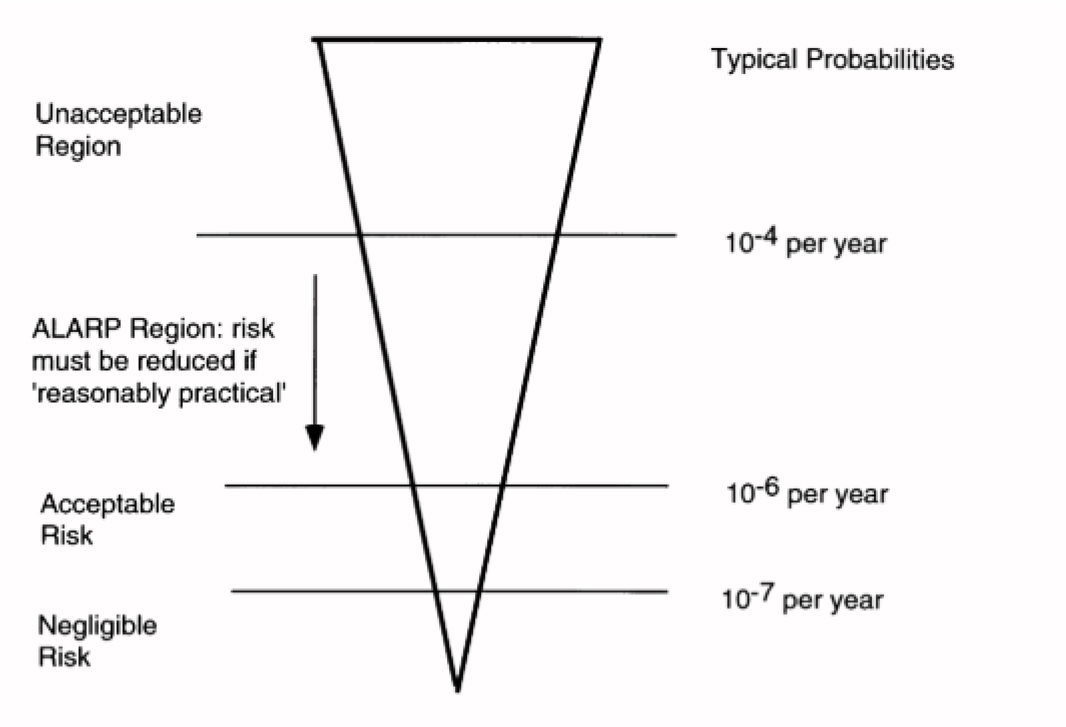

Figure 11: Conceptual representation of the ALARP approach (Melchers, 2001).

In the Netherlands the ALARP technique is the leading technique in providing norms for the water safety. The basic safety standard is described in terms of the local individual risk of a person living in a certain area passing away due to flooding each year. The 'basic safety norm' is a maximum of 1/100,000 individuals per year to drown due to flooding . To give an example: in the area within dike ring 48 in the Netherlands (area near Ossenwaard and Lobith*)* this results to an acceptable number of casualties of is 1-2 per year due to flooding (Maaskant et al., 2019). Another example where the ALARP approach is applied is the failure probability of the *Maeslant Barrier*, the biggest storm surge barrier of the Netherlands. It has a probability of failure of 1/100 times it is deployed, which is expected to increase to 1/1.000 with technological improvements (Kind et al., 2019).

Regarding critical infrastructure safety there are not a lot of norms. Table 1 shows for which critical infrastructures there are legal norms which set a minimum functionality standard. If these norms apply, they are set by government and adhere to the operators of the network.

Table 1: Dutch critical infrastructure systems with laws and regulations regarding allowed probabilities of failure (Bles et al., 2020)

Critical Infrastructure system	**Legal norms apply**
Electricity	yes
Natural gas	yes
Oil	Partially*
Crisis communication channels	no
Public communication channels	yes
Drink water	yes
Waste water	Partially*
Health	Partially*

Surface water	no
Rail and roads	no
Chemicals	Partially*
Nuclear	yes
Infectious substances (GMO's)	no

* A partial legal norm means that within other laws (for example the Environmental Act) this infrastructure is adopted and has for example a reporting duty.

2.4.2 Norm setting to evaluating risks

Lastly a common method used by network operators to evaluate whether or not to accept certain risks is to use a risk matrix. An example of this is presented in figure 12. These matrices are standards set by the companies but often rely on qualitative analysis and expert judgement. They are not legally binding. The disruption of the infrastructure is evaluated per hazardous event with a certain likelihood and its associated consequences. If this is situated in the red area, which means a hazardous event with a high likelihood of occurrence and high consequences, measures should be proposed (Bles & Özbek, 2018).

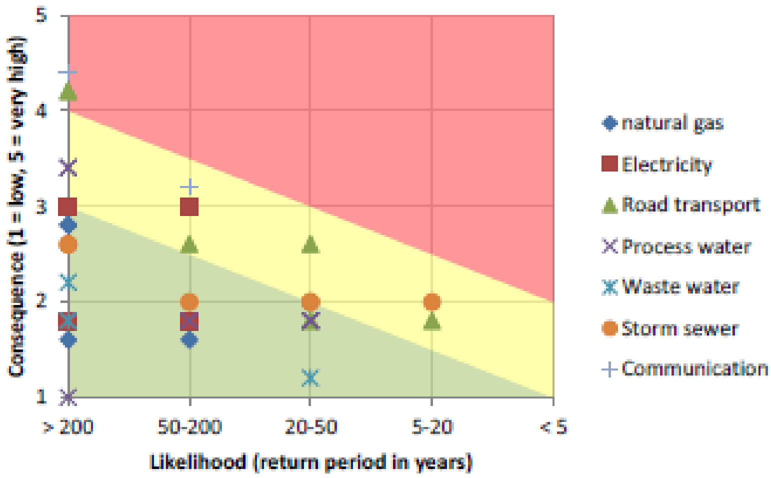

Figure 12: Example of a risk matrix for the risk of disruption of certain critical infrastructures (Bles & Özbek, 2018).

2.4.3 Conclusion

Defining norms for failure of critical infrastructures remains difficult. Often the ALARP technique is applied, but it remains indefinite how the lower and upper bound of the acceptable chance of failure should appropriately be established. Some legal norms apply for the functioning of critical infrastructures, but certainly not for all of them. Operators of critical infrastructures often use a risk matrix which includes a certain self-selected norm, to evaluate whether or not certain risks are acceptable or not.

2.5 How can the user be included in establishing a desired level of resilience?

From the previous section can be concluded that there exist some norms or rules regarding the minimum service level of some critical infrastructures. These norms area established often using the ALARP principle. However, it makes sense to include the user of the infrastructure in deciding what a minimum service level would be. Not much research has been conducted on this topic yet. Though, within the research project IMPROVER, funded by the Horizon 2020 research and innovation program of the European Union there have been some case studies. The IMPROVER project (subtitle Improved Risk Evaluation and Implementation of Resilience Concepts to Critical Infrastructure), acknowledges that there is no common European methodology for measuring resilience or implementing resilience concepts (European Commission, 2020). Part of the research consists of case studies exploring how to research and establish tolerance levels of users of critical infrastructure disruption. It is suggested to use the minimum level of service and rapidity of restoration as indicators to measure the public tolerance to disruption. The case studies all use a questionnaire approach, which are used in three of the researches to establish so-called tolerance triangles.

2.5.1 IMPROVER case studies and methods

The first research (Petersen, Fallou, Reilly, et al., 2018) assesses public expectations of critical infrastructures during crisis in general. An online questionnaire was distributed and 403 people in the study areas Barreiro (Portugal), Oresund Region (Sweden/Denmark), Oslo Harbour (Norway), and France, and filled it in using self-selection. Three types of critical services were subject of the research: the water network, road network and essential goods. For each service a few alternatives were presented following from a disruption. For example one of the questions was if, after a disaster people would tolerate the following disruptions to the usability of transportation: a) transportation for emergency services only; b) alternative means; c) local diversion; d) reduced capacity or frequency of service; e) I would not tolerate any disruption. The second question was whether people for which duration people would accept this reduced service, specified in 'years', 'months', 'weeks', days', 'hours', or 'not at all'. The tolerances are visualized in figure 13.

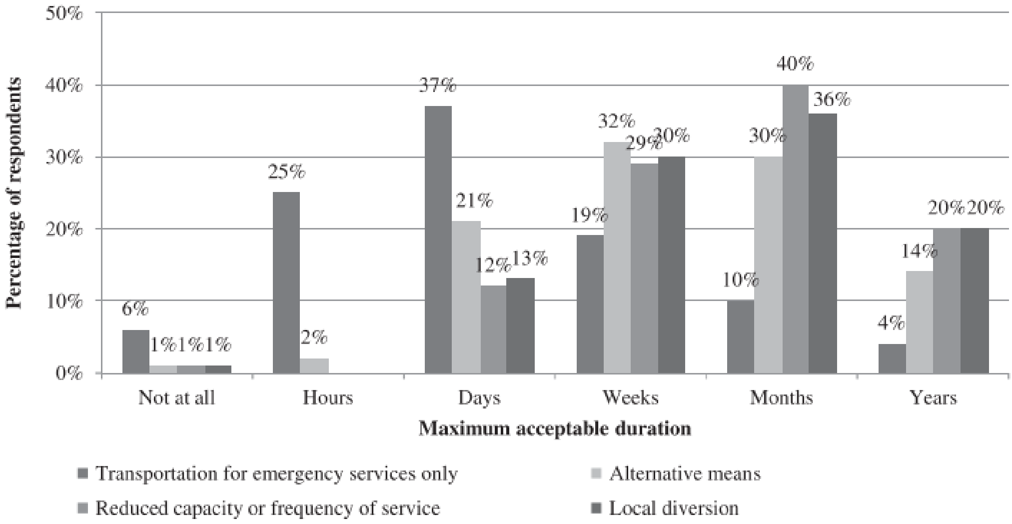

Figure 13: Visualization of the tolerances to disruption of the road network. (Petersen, Fallou, Reilly, et al., 2018).

In this research also variation in socio-demographic factors were taken into account. The main outcome of the research was that the 'expectation gap' between service of network operators during crisis and what people expect, is smaller than suggested by previous research. Limitations and improvements to the methodology are summarized and further research on this topic is encouraged because the authors believe, once known, these public expectations could be used to set appropriate targets for implementation of critical infrastructure resilience. How exactly is not mentioned.

The second research (Petersen, Fallou, Carreira, et al., 2018) is a pilot case study with the same set-up as the previous one, but then focused on the Oresund region. A specific situation, the migrant crisis in 2015, led to an increase in journey time of about 30 minutes, because customs needed to check all travel documents of the travellers. Because the infrastructure users of the rail network had experienced this disruption, it seemed an appropriate area. 88 participants filled in a questionnaire using convenience sampling. The question set-up was the same as in the previous research, asking *if they were willing to accept* the four alternatives of transportation services, and for what duration ('hours', 'days', etc.). The main conclusion again was that tolerances are higher than expected, even for longer periods of time. The main limitation was the small sample group being not representative for the population in the area.

The third research (Petersen, Lundin, et al., 2020) demonstrates how tolerance triangles can be established. The study area was Barreiro, Portugal, and this time a reduced functioning of the potable water network was researched as a consequence of the fictious event of an earthquake. A representative sample of respondents (n=1005) was collected to fill out a survey. Tolerance triangles were established by asking people how much service disruption they would tolerate and for what duration. By questioning specific durations, contrary to the previous pilots, they were able to establish tolerance triangles, of which an example is given in figure 14. The Y-axis shows the cumulative percentage of people who would tolerate the duration of water shortage. These tolerance triangles are comparable to resilience triangles as described in the previous section on quantifying resilience.

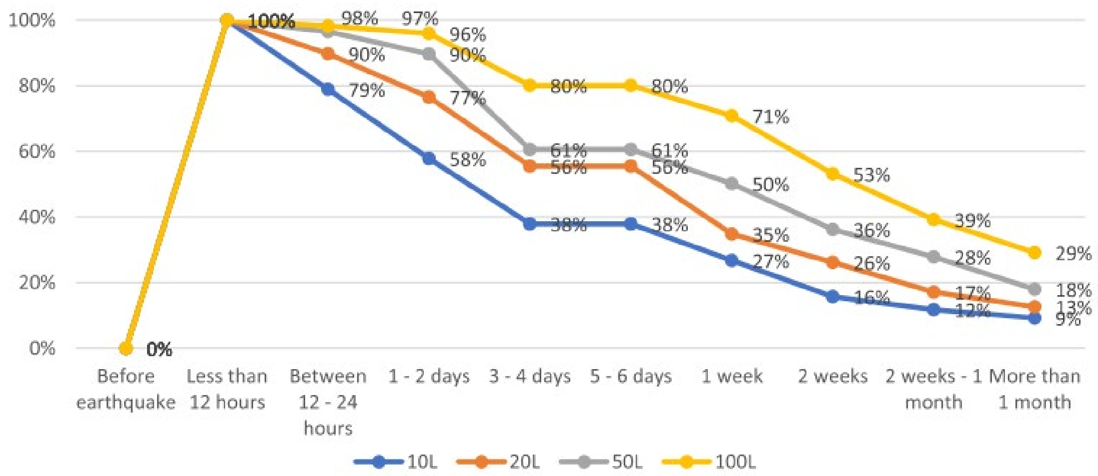

Figure 14: Tolerance triangle for a given amount of water per person. (Petersen, Lundin, et al., 2020).

By taking into account socio-demographic characteristics, also differences between vulnerable groups were accounted for. This research is the first quantification of a desired level of resilience of an infrastructure, and has the potential to be compared to the actual level of resilience of the infrastructure.

The last research (Petersen et al., 2019), a pilot case study regarding the Hungarian highway, takes this next step. It demonstrates again the questionnaire-based methodology to determine public tolerance levels but now shows how to evaluate this with regard to the technical resilience analysis of the same system. In order to evaluate this, the public perception of their coping capacity must have the same metric as the current resilience metric if the infrastructure. Two types of hazardous event were used: a heavy snow storm preventing people to use the highway and a collision leading to increased travel times due to deviations. In total 116 respondents filled in an online questionnaire using self-selection and again socio-demographic characteristics were included in the study. The research proposes to compare the tolerance triangle with the resilience triangle, as depicted in figure 15. The red area under the tolerance triangle shows where there is room for improvement.

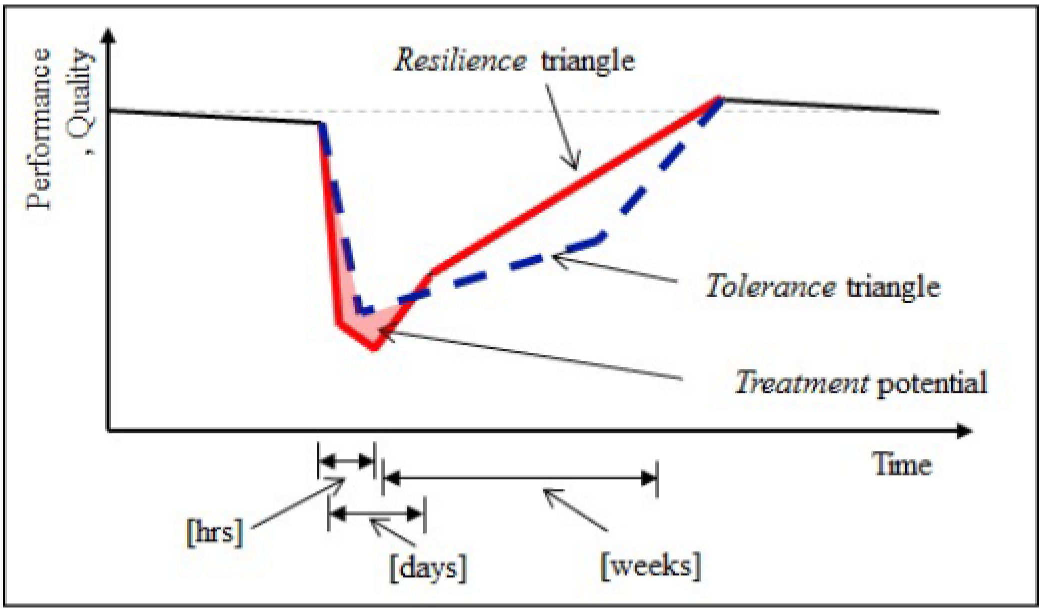

Figure 15: Schematic representation of a resilience triangle (Petersen et al. 2019).

The metric used to indicate performance quality is 'additional travel time' (inverted on the y-axis, zero being the highest value representing full performance). A weighted average of the respondents is used to arrive at the average acceptable additional travel time for each specific duration of the disruption. To quantify the resilience of the infrastructure itself the ITRA (Technical Resilience Analysis) methodology is used (Honfi et al., 2018), which led to the resilience triangle in the form as described earlier. Because it is plotted in the same graph as the tolerance triangle, the two can be compared. However, the ITRA analysis had not been fully carried out, thus the results of the curve are purely to demonstrate how the comparison can be made. The authors evaluate the methodology as promising and especially valuable for the network operator to give input on the tolerable amount of service reduction during a crisis.

2.5.2 Conclusion

This section gives insight in state of the art research regarding measurement of tolerance to disruption of critical infrastructures. The four case studies present a survey-based methodology which in each step is refined to finally propose a methodology how a desired level of resilience can be compared with the current level. Nevertheless the full method is not properly demonstrated due to lack of information on the resilience analysis. Also the response rates to the questionnaires remain rather low, except for the case study in Barreiro. Lastly, the question remains uncertain whether it is appropriate to ask respondents about their tolerance level, since this is might be subject to a self-cost-benefit evaluation of the respondent. This aspect is not reflected upon by the authors.

Concluding, the presented case studies propose a promising methodology but need more research to be validated. Overall, the topic of how to set standards for the minimum functioning of critical infrastructures and maximum duration of disruption is an under-researched area. The authors propose to use tolerances of the user as input for these standards.

2.6 How can resilience improving measures be classified, assessed and selected appropriately be selected?

This chapter concludes with some background on how certain measures can be assessed or chosen. Extensive lists to improve resilience of critical infrastructure systems exist, but choosing the best option remains difficult. For example within the EU funded project INTACT (subtitle 'On the Impact of Extreme Weather on Critical Infrastructures') a complete lists of resilience improving measures for all types of infrastructures is composed (Blied et al., 2015). The measures are clustered according to the type of infrastructure and the phases of a disaster cycle as identified before. The phases as formulated in this research are mitigation, preparedness, response, recovery and reconstruction, and originate from the crisis/disaster management cycle. This cycle is often used to classify resilience improving measures. The cycle is presented in figure 16.

Figure 16: The Disaster Management Cycle, filled in for flood risk mitigation(Most & Marchand, 2017).

Other measures the so-called 'no-regret measures'. These are in general low-cost, high-impact measures which are always worth it to implement. This could for example be to establish contingency plans and train first responders to act in crises (Van Ruiten et al., 2016).

Another way to classify measures is according to the properties of resilience, as identified earlier as well. For example, measures increasing robustness or redundancy of a system. The effect of these type of measures can be assessed by simulating the reduced disruption a hazard has on a network. For example by creating multiple resilience triangles for situations with or without certain measures, as proposed by Murdock (2017) and de Bruijn et al. (2019). With this method, the increase of resilience due to the measure can be quantified, and makes it easier to compare and select different measures. Also in the research by Pregnolato et al. (2017) first the current level of resilience is quantified and after that effect of measures is quantified and monetarized. In literature it is also common to provide a decision support system for selecting measures to improve resilience of critical infrastructure. An example is proposed by Bush et al. (2004), where the increase in utility is modelled after installing a measure or not. The highest improvement in utility relative to the costs is then the selection criterium.

The previous examples show quantitative methods to evaluate resilience improving measures and are examples of a Cost Benefit Analysis. Other methods to do this are to conduct a Multi Criteria Analysis, a Life Cycle Costing analysis, or a Cost Effective Analysis (Bles et al., 2019). The type of evaluation method depends largely on the level of detail that is required, what data is available and the objectives of the analysis in general. For example a full Cost Benefit Analysis requires a lot of data to be able to convert the costs and benefits of a measure into monetary terms, whereas a Multi Criteria Analysis is mainly a qualitative method which might be more appropriate to build consensus among stakeholders.

2.6.1 Conclusion

Proposing measures to improve resilience of critical infrastructures is a complex task. Classification of measures can be done in many ways, but taking into account the temporal dimensions of resilience is advised. Evaluating which measures to choose can be done quantitatively if the current level of resilience and the effect of the measures is assessed and quantified properly. Also qualitative methods exist to select the appropriate resilience improving measures.

2.7 Concluding literature section

Since there is still no consensus on the definition of critical infrastructure resilience, this chapter starts with presenting several definitions and establishes one chosen for this research. An important shift is observed in defining critical infrastructure resilience. Whereas it used to describe the asset delivering the essential service or good, it is now emphasized to focus on the critical service which should be protected. Moreover, this shift includes accepting that the vital functions cannot be protected to all types and severities of hazards. The aim should be to deliver a continuous minimum level of service during a crisis.

Critical infrastructures are always part of other infrastructure networks and are therefore interdependent on each other. When a disruption occurs to one system, this can lead to cascading effects to other systems. When describing resilience of critical infrastructures often the following temporal phases are distinguished: before the event (prepare/plan for), during the event (resist / absorb / accommodate), recovering from the event and after the event. Properties of a resilient system often found in literature are: robustness, redundancy, rapidity and flexibility. These properties are also often used to assess resilience. Quantification of resilience is more and more done by using a resilience triangle, which includes the temporal dimensions of resilience.

Defining norms for failure of critical infrastructures remains difficult. Often the ALAPR (as low as possible) technique is applied, but it remains indefinite how the lower and upper bound of the acceptable chance of failure should appropriately be established. Operators of critical infrastructures often use a risk matrix which includes a certain self-selected norm, to evaluate whether or not certain risks are acceptable or not.

The IMPROVER project is one of the first researches on how users of critical infrastructure evaluate disruption of the service. A questionnaire-based method is presented, and the concept of tolerance triangles are introduced. Nevertheless the full method is not properly demonstrated due to lack of information on the resilience analysis. The authors recommend to include users' tolerance levels in establishing a desired level of resilience. The project serves as a starting point for the case study conducted in this thesis.

Proposing measures to improve resilience of critical infrastructures is a complex task. Classification of measures can be done in many ways, but taking into account the temporal dimensions of resilience is common. Evaluating which measures to choose can be done quantitatively if the current level of resilience and the effect of the measures is assessed and quantified properly. Also, qualitative methods exist to select the appropriate resilience improving measures.

3. Case Introduction

This chapter introduces the methodology of the case study and elaborates on the three different steps. The final section presents the main features of the study area.

3.1 Case study methodology

The aim of the research is to demonstrate a methodology to incorporate the users' perspective in the resilience assessment of critical infrastructures. This is done to be able to set norms to which the resilience of the infrastructure should comply. To demonstrate the methodology a case study approach is chosen. In general, the problem around the resilience of critical infrastructures is one which is very complex and has not been studied a lot yet. Because there is still little knowledge available, the subject still needs to be explored, for which the use of case studies is recommended by Verschuren & Doorewaard (1999). Also a case study is an excellent method when one faces a so-called *wicked problem*. Such a problem was first described by (Rittel & Webber, 1973). It emerges when there is no consensus on relevant norms and values, nor is there consensus or certainty about relevant knowledge. This also applies to the study on how to attain resilient critical infrastructure networks: there is no consensus yet on what the standard is of a resilient system, nor is there consensus on how to achieve this. Later on, this theory has been further worked out by Hisschemöller & Hoppe (1995). Wicked problems are also called *unstructured problems.* To study them, it is recommended to take a *learning strategy* (de Jonge, 2009). Indeed, while carrying out the research much insight was gained in how the method should be improved. Hence the evaluation of the case study and method might be as important as its' results.

3.2 Research steps

The case study follows four steps, as visualized in 17. Case study part I, II and III are research projects on their own. In the corresponding chapters 4, 5 and 6 a separate methodology section is presented as well as separate results and conclusions.

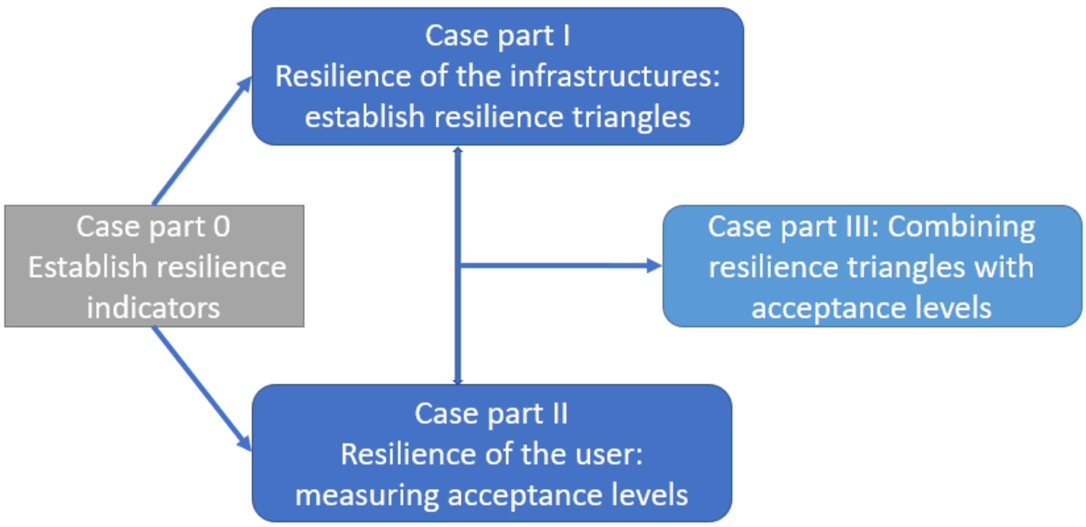

Figure 17: Overview of the case study approach.

Step 0: Establish resilience indicator

Previous research underlines the usefulness of resilience indicators, and emphasises to define them clearly (de Bruijn, 2004; Reitan et al., 2018). The indicator for this research is the *number of people not accepting disruption*, measured in the unit 'people'. This indicator consists of four dimensions, which are listed in Table 2. The first dimension is the severity of the rainfall event which is measured in millimetres of rain. Five different types of rainfalls are chosen. The second dimension is the recurrence time of these rainfalls. These two dimensions are thus connected. This is elaborated on in chapter 4. The second dimension is the type of network. In this research the focus lies on two networks: the road network and the electricity network. Three other networks were analysed as well: the mobile network, the accessibility of hospitals and the accessibility of supermarkets. However, these were not elaborated on fully in this thesis. The last dimension is the duration of the disruption, measured in hours.

Table 2: Overview of used metrics and dimensions in the resilience quantification

	Part I: Infrastructure resilience	**Part 2: User resilience**
Metric	Number of people affected by disruption (#)	Chance a person will not accept the disruption (%)
Dimensions		
1 + 2	Severity of event (mm rainfall)	Recurrence time of event (year)
3	Type of network	Type of network
4	Duration of disruption (hours)	Duration of disruption (hours)

Step 1 Resilience of the infrastructures

Different rainfall events are simulated in a hydrodynamic model to analyse the flooding patterns in the study area. With spatial analysis software overlays are made with the critical infrastructure networks. This enables to identify disruptions to the network. Using a population density map the number of people affected by this disruption is quantified. Calculating the number of people disruption over time enables to establish resilience triangles.

Step 2 Resilience of the user

A questionnaire based approach was used to capture the acceptance levels of the infrastructure user. A survey was developed and distributed to inhabitants in the case study area. This survey involved evaluating different scenarios of disruption to infrastructures. The likelihood of someone not accepting the given disruption was researched using ordinal regression.

Step 3 Combining the resilience of the infrastructure and the user

By multiplying the acceptance rates with the number of people affected, the number of people not accepting the posed disruption is calculated. This is visualized in acceptance triangles. The maximum number of people not accepting a disruption is studied per event, and some scenarios are included to elaborate on the possibilities of the methodology.

3.3 Study area

The city centre of The Hague, the Netherlands is chosen as the study area of this research. The area is presented in figure 18 including the neighbourhoods. The centre of the city is located approximately 4 km from the west coast and has a total area of about 9 km^2. The case study area has a population of approximately 176,000 people. Appendix A provides a height map of the case study area. The north west side lies about 3 meters above sea level but towards the south east side it slopes downwards to around sea level. The neighbourhood Huygenspark is the lowest lying area, some places around 2.5 meters below sea level. The higher areas have a sand surface, the lower areas have a peat soil.

This area was chosen because a previous study on the direct and indirect effects of a flash flood in this area had been conducted prior to this research in 2019. In that study a panel group of critical infrastructure operators was brought together to evaluate the scenario. The network operators were provided with a water depth map of the area after a simulated rainfall of 70mm in one hour. During the workshop vulnerable networks and water depth thresholds were established. These networks and thresholds are used as an input to this research (Deltares, 2019).

Figure 18: Map of study area.

3.4 Conclusion

This chapter presents why a case study is chosen as a methodology to answer the research question. Furthermore, it introduces the different parts of the case study and the related dimensions which are chosen. Lastly it presents the case study area, which is the city centre of The Hague.

4. Case Part I Resilience of the infrastructures

4.1 Introduction

This chapter aims to analyse the resilience of the critical infrastructure networks in The Hague. Firstly an overview will be given of the direct and indirect effects of a flood due to heavy rain on several infrastructure networks. This leads to the conclusion that four critical networks will be assessed: the road network, electricity network, the accessibility of the hospital HMC Westeinde and the accessibility of supermarkets and grocery stores. Secondly the methodology of the research will be introduced. This section contains information on the used software to simulate rainfall events and a description per infrastructure of how the disruption is calculated. A subsequent section presents the results of the research. They consist of inundation maps of the study area and disruption maps per infrastructure. Finally, the conclusion summarizes the results and the discussion elaborates on the limitations of this research.

The main research question that is addressed in this chapter is:

> How resilient are the critical infrastructure networks of The Hague to flooding due to heavy rainfall?

Sub questions are:

- Which parts of the city will get inundated due to various rainfall events?
- What are the consequences for the critical infrastructure networks?
- In what areas will disruption to the networks occur?
- How many people will be affected by the disruption?

This chapter does not provide advice on improving the resilience of the networks, nor does it propose measures to reduce flooding in the area. The aim is to quantify the resilience of the networks which serves as input for later chapters.

4.1.1 Direct and indirect effects of the flood

Previous research on the consequences of a flood due to heavy rain in the study area of The Hague serves as a starting point for this research. During a workshop with different stakeholders of critical infrastructure networks in the area, a flood scenario was analysed in detail (Deltares, 2019). Some vulnerable networks and their thresholds were established, which are used as input. These thresholds indicate the water level on street which will disrupt the system.

The difference between direct effects of a hazard on critical infrastructure networks, and indirect effects (also called cascading effects) is pointed out in the literature review. The workshop revealed four networks which will probably directly be affected by a flood: the road network, the electricity network, the mobile network and the hospital HMC Westeinde. The hospital is part of the critical infrastructure of health services. In this research the accessibility to supermarkets is added, which can be seen as critical infrastructure to provide food to inhabitants. The direct and indirect effects of a flood are visualized in figure 19.

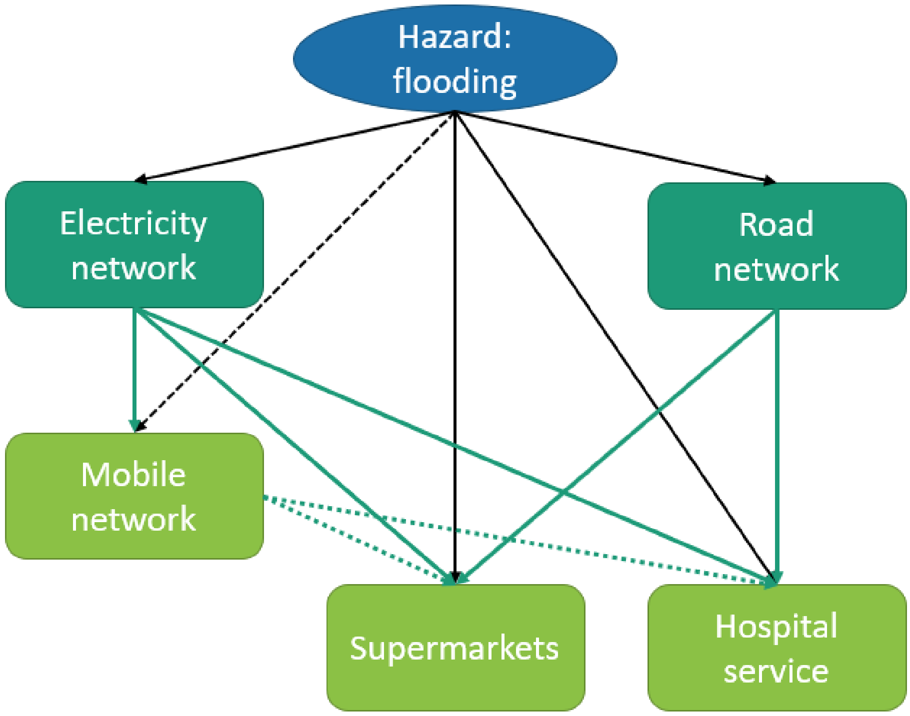

Figure 19: Visualization of direct and indirect effects of flooding to the critical infrastructure networks.

The black arrows in the figure point from the hazard to the five critical infrastructure networks and indicate the direct effects. The green arrows indicate the cascading effects. The electricity network, road network and mobile network will thus cause indirect effects. Though previous research pointed out that the mobile network might be vulnerable to flooding (Deltares, 2019), this is questioned in this research. The direct effect of flooding on the mobile network will be limited, since most antennas are located on top of buildings (Antennekaart.nl, n.d.). An antenna is reliant on the electricity network and can last for about two hours during an electricity outage. But, since the density of the antennas is very high in the study area, it can be assumed that the consequences of this indirect effect are limited. Appendix B provides a map of antennas is the study area, which points out this redundancy. Thus, in this research it is assumed that the mobile network will not be affected by a flood due to heavy rainfall. The direct and indirect effects of the mobile network are visualized in figure 19, but with a dotted line.

This research will focus on the direct effects of flooding on the road and electricity network and the accessibility of grocery stores and the hospital in the area. Moreover, the cascading effects of the disrupted roads and electricity outage on the accessibility of the supermarkets and the hospital will be analysed.

4.2 Methodology

In order to establish how many people will be affected by network disruption as a consequence of flooding, the following method is followed. Firstly, a 3D model of the city is used to simulate the flooding as a result of various types of rainfall. This leads to inundation maps. Secondly, these maps are combined with geospatial data of the critical infrastructures and the critical threshold. The combination leads to predictions how much disruption in the network can be expected. The last step is to combine that with population density data to calculate the number of people who are affected by the disruption. The workflow of this process is visualized in figure 20.

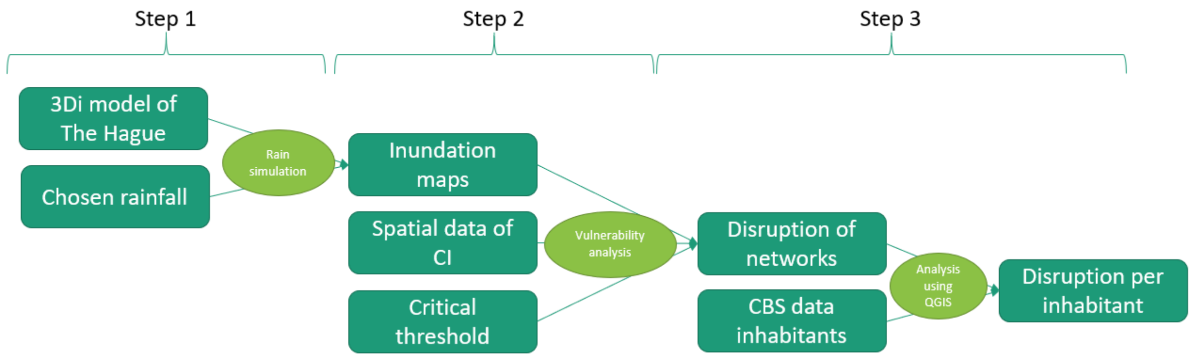

Figure 20: Workflow to quantify resilience.

4.2.1 3Di hydrodynamic model

This research uses the hydrodynamic simulation software 3Di, to predict the location, intensity and duration of floods due to heavy rainfall in the city of The Hague. The software is developed by a consortium of the following companies: Nelen & Schuurmans, Deltares, TU Delft and Stelling Hydraulics (3Di Water Management, n.d.). In brief, the model in this tool can be seen as a simple digital twin of the city combined with hydrodynamic models to simulate the movement of water through the city. 3Di is well suited to model urban flooding and is often used for research on flood mitigation worldwide (Al Ruheili & Radke, 2020; Dahm et al., 2014; Hadidi et al., 2020; Ju et al., 2017).

The software is based on a calculation method introduced by Casulli (2009) to solve shallow-water equations, which describe the flow of water in a set of differential equations, using a so-called sub-grid method. This method allows to consider high-resolution grids, but by aggregating the information in a coarse grid, calculations are accelerated (Ju et al., 2017). From these calculations, the water levels and velocities are obtained. A second noteworthy aspect behind the 3Di software is that it uses a quad tree technique developed by Stelling (2012), which enables us to use both small and large grid cells in the model. Small grid cells are used when variation is high and detail is needed – in case of high elevation differences, for instance. For areas with low variation, a coarse grid suffices (Dahm et al., 2014).

The model in the 3Di software is based on different input components. Information on elevation (Digital Elevation Model), friction and infiltration are loaded into the model in 2D. The sewage system, including channels, culverts, manholes and infiltration trenches, is added as well in 1D (consisting merely of lines and points). The model has spatial boundaries, usually chosen on locations of existing hydrological boundaries, such as a levee, an elevated road, or a waterway. In- and outflow of water through the boundaries, for example in scenarios of a river crossing the area, can also be defined. Lastly, the type of rainfall event has to be defined, including the duration and volume (Hadidi et al., 2020).

By solving the shallow water equations, the software will calculate the water levels and velocities at a given time step per grid cell, which enables us to produce several flood maps at chosen points in time during or after the simulated rain event. It is also possible to visualize cross-sections, calculate water heights within pipes or culverts at certain times, or calculate cumulative discharges through the sewage system.

4.2.2 Step 1a Configuration of 3Di model

The model of the centre of The Hague was made by engineering firm Nelen&Schuurmans, who obtained their data about elevation, friction, infiltration and sewage system from the municipality. The 3Di software was accessed through a 'live-site'. This means that the digital model and the software could be accessed through the browser, but is owned by the engineering firm and stored and ran on one of its servers. This simplifies the use of the software, but also limits the possibilities to alter the model. Figure 21 shows a screenshot of the 'live-site' where the model boundaries are visible.

Figure 21: User interface of the 3Di software.

In consultation with the software owners (engineering company Neelen & Schuurmans), the model boundaries are chosen along waterways which serve as hydrological barriers as the water in the barriers is lower than the overall water level. The area is enclosed on the west and east side of the model by the Laak channel ('*Laakkanaal*'), on the east side by the *Oranjesingelsgracht/Koninginnegracht* and on the north side by the *Segbroeklaan/President Kennedylaan* and the parks *Zorgvliet* and *Scheveningse Bosjes.* The area slopes downwards from north to south. Hence, it is less important that the boundaries on the northside are hydrological barriers, since the water will flow southward naturally. This is visible in the Digital Elevation Map which is used as input to the model (presented in appendix A).

As mentioned before, the model uses a grid with varying grain sizes, depending on the level of detail which is required for the calculations. This is referred to as the quad tree technique. An examle of the grid is visible in figure 22, at the location of the hospital HMC Westeinde. The level of detail around the hospital and the access roads is high, whereas it is lower in the more uniform neighborhoods and squares.

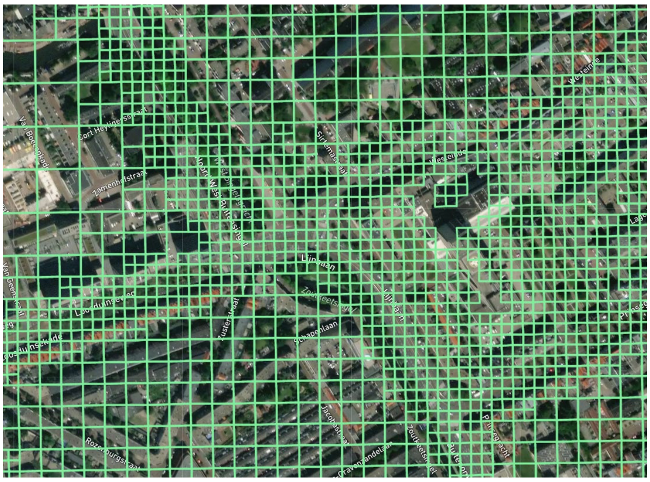

Figure 22: Example of the used quad tree grid at the location of the hospital HMC Westeinde.

As visible in figure 21, four pumps are added manually to the model in the user interface. Two of them exist in the real world but have a different capacity. The other two simulate system boundaries. The pumps were added in order to improve the validity and make the model more veracious. A problem arose when modelling rainfall of 35mm per hour and more. It was found that even under this relatively low intensity, rains the canals on the edges flooded completely. Because the edges of the model were designed as 'closed' boundaries, the water stayed inside, which lead to unrealistically high water levels around the edges of the model. It also caused a long duration of flooding in the centre of the model. In reality there are no boundaries around the model, and water can flow out of the area freely. In order to approach this the pumps where installed so water could 'leave' the model, as it does in reality. The location and flow rates were chosen in consultation with the engineering firm and an urban hydrologist. Table 3 gives the locations and chosen flow rates of the pumps.

Table 3: Location of added pumps and capacity.

Location of added pumps	Flow rate
1. North end of the model, *Verversingskanaal*	3 m3/second
2. Southeast end of the model, *Laakkanaal*	3m3/second
3. Rail underpass *Prins Bernhardviaduct*	1m3/second
4. Rail underpass *Callandstraat*	1m3/second

The first pump is simulating a pumping station located north from The Hague: the *Drs. P.H. Schoute* pumphouse which has a flow rate 19.5m3/second (De Nederlandse Gemalenstichting, n.d.). The drainage area of this pump station is about 6 times as large as the area in the model (rough estimation), resulting in a flow rate of 3.25m3/second of water leaving this model from the north side. A second estimation to the pump capacity of this area can be derived when looking at pump capacity estimations for the whole dike ring, as estimated by Wagenaar (2012). The Hague lies in the area of dike ring 14, which if completely flooded can be pumped dry with a capacity of 15mm per day. Given that the area of our model is approximately 9km^2, this gives a capacity of 1.56m3/second. This seems a lot lower, but it is likely that within a city more pump capacity is present and the order of magnitude matches.

However, these numbers do not take into account the fact that water can flow freely out of the model due to the downward slope to the south. Hence, in consultation with an expert in urban hydraulics it is agreed to make an overestimation of the pump capacity to account for this. A total of 8m3/second is to be pumped out of the area, to be distributed at different points in the model.

Looking at the flooding patterns from the initial model, there are two rail underpasses which keep flooding. Checking the model for simulated pump capacity, and consulting with a civil servant from the municipality of The Hague, it turns out there are new pumps installed at those locations which are not in the model. For the rail underpass *Prins Bernhardviaduct* the modelled capacity is 0.018m3/second, which in reality is 0.075m3/second. The rail underpass at the *Callandstraat* has a modelled capacity of 0.091m3/second which in reality is 0.167m3/second. Two additional pumps will be placed at these locations. In the 'live-site' it is possible to add pumps manually, but the capacity can only be specified per m3/second (thus, 0.5m3/second is not possible, only 1m3/second).

Taking all these uncertainties and limitations into account the strategy, four pumps were added to the digital model at the locations as mentioned in table 3. This probably gives an overestimation of the pump capacities in both the tunnels and around the borders of the model. Thus, if these areas still get flooded in the simulations with an overestimated pump capacity, these areas are sure to be vulnerable to flooding.

The model alterations are checked and validated with an expert at the municipality of The Hague from the water and sewage department. Also, the results are validated by comparison with another rainfall simulation software Tygron of a smaller area. The results of that model indicate the same vulnerable areas and comparable water depths. The Tygron results are presented in appendix C.

4.2.3 Step 1b Rainfall simulations

The types of rainfall which are chosen to simulate are listed in table 4.

Table 4: Types of rain events simulated in the 3Di model.

	Recurrence time (1/ n year)		Selected points in time
Type of rainfall	Scenario 2020	Scenario 2050	
18.9mm - Rainfall design 8	2	1*	t=1,
35.7mm - Rainfall design 10	10	5*	t=1, t=4, t=7
50mm – 1 hour	50	25	t=1, t=4, t=7 t=10
70mm – 1 hour	200	100	t=1, t=4, t=7 t=10 t=13
90mm – 1 hour	500	250	t=1, t=4, t=7 t=10 t=13

* Estimated values, based on the predictions of changing recurrence times of the other rainfall types

The recurrence time of the rainfall events are predicted by the Royal Netherlands Meteorological Institute for the current climate (2020) and for a changing climate in 2050 (KNMI, 2015). However due to uncertainty in the models there are different scenarios possible for the changing recurrence times. The recurrence times presented in table 4 for the 2050 scenario are the 'worst case' predictions (Kennisportaal Klimaatadaptatie, n.d.).

The first two rainfalls are artificial rainfall events which are composed by the RIONED foundation and are used as a guideline to design sewage systems in the Netherlands. These rainfall designs vary in duration and intensity. Every timestep of 5 minutes has a different intensity with either a peak of rain somewhere at the beginning or the end of the event. Rainfall design 8 takes 60 minutes and has its peak at the end, while rainfall design 10 takes 45 minutes and has its peak in the beginning. The recurrence times of these rainfalls are respectively 2 years and 10 years, as predicted by RIONED in 2019 (RIONED, 2019). There is no prediction how much the recurrence time will change according to a changing climate.

The other three simulated rainfalls are continuous in intensity throughout the event. Though it is sure this is an unrealistic type of rain profile, there will always be variation in intensity, the 70mm/hour and 90mm/hour continuous rainfalls are used throughout the Netherlands in the climate adaptation stress tests and were hence chosen for the simulations. To get a complete overview, the 50mm continuous rainfall was added.

The column 'selected points in time' in table 4 refers to the time after the rainfall at which the flood in the city is studied. The start of the rainfall is time 0, and for all rain events (including rainfall design 10 which only takes 45 minutes!) the moment directly after the rainfall is time=1. Thus, time=4 means there has been a dry period for three hours after the rain event. For every point in time a new map needs to be exported and analysed. Thus, for efficiency reasons the amount of selected points in time is kept as low as possible while still being able to see trend lines. The two rainfalls with the lowest intensities were stopped when most water had left the model and it could reasonably be assumed there would be no disruption. The simulations of the 50mm rainfall was stopped at t=10 because at that point only water was present in tunnels. For the 70mm and 90mm rainfall, the water remained in the model over 13 hours, but after this the simulation was stopped due to time constraints.

4.2.4 Step 2a Inundation maps

When the simulation of a particular rainfall is ran in the live-site of 3Di, the results can be exported to a data and analytics platform called Lizard. In this environment, accessible through the browser, all data of the simulations is stored and archived (source, source). From this platform all necessary data from the 3Di software can be exported to QGIS. For this research only the water depth maps are exported, but also for example maps with the maximum water level or flow rate can be retrieved.

In total 18 maps were exported of the five different rainfall events of different durations as shown in table 4. These maps are a Tagged Image Format (TIF), and can be loaded in QGIS. Using the styling band 'singleband pseudocolor' the data can be visualized as inundation with different water levels.

4.2.5 Step 2b Thresholds

Previous research in the case study area identified several thresholds for functioning of critical infrastructures(Deltares, 2019). Relevant thresholds mentioned in the report are listed in table 5.

Table 5: Thresholds values for functionig of the road system with different vehicle types (Deltares, 2019).

Vehicles using road network	Threshold
Trams	10 cm
Cars, ambulances	30cm
Fire truck	50 cm

This research uses the 30 cm threshold for road disruption, which has the consequence that cars and ambulances cannot use the road anymore.

The threshold for electricity outage due to flooding of power boxes was obtained from internal documentation from Stedin. Because the thresholds varied in the document, this was later validated with the risk analyst from Stedin. The current threshold which is used in flood analysis is 30 cm, which is also used for this study.

To attain polygons in QGIS which hold areas which are flooded above the threshold value, the following workflow was used:

1. The exported inundation maps are raster files. Using the Raster Calculator from QGIS, the areas with water depths of 30cm or more are coded as 1, other are 0.
2. These raster files are converted to polygons using the 'polygonise (raster to vector)' tool.
3. Polygons with a zero value are selected and deleted in the attribute table.
4. The remaining polygons are very messy, meaning the forms are complicated. In later analysis, QGIS will give an error for some of these shapes saying 'geometry not valid'. To omit this problem and speed up the calculations later on the forms are simplified by adding a round buffer of 3 meters.

An example of such an inundation polygon is given in figure 24. In this figure it is clear that the canals are also indicated as flooded areas. This makes sense, because a lot of rain will flow from the streets to the canals, increasing the water depth of the canals. If more then 30cm extra water accumulates in the canals, these will also count as inundated areas. However, when taking a second look it is visible that these canals are uninterrupted by bridges. This is not realistic, because bridges will have a higher elevation then the canals, thus are less likely to flood. When studying the digital elevation map which was used as input to the 3Di model, it turns out that the canals are indeed uninterupted by bridges, which is not realistic. This is visible in figure 22. This has consequences on the reliability of the inundation polygons, especially when they are used to predict the disruption of the street network, and the accessibility of locations. How this problem is corrected is explained later on.

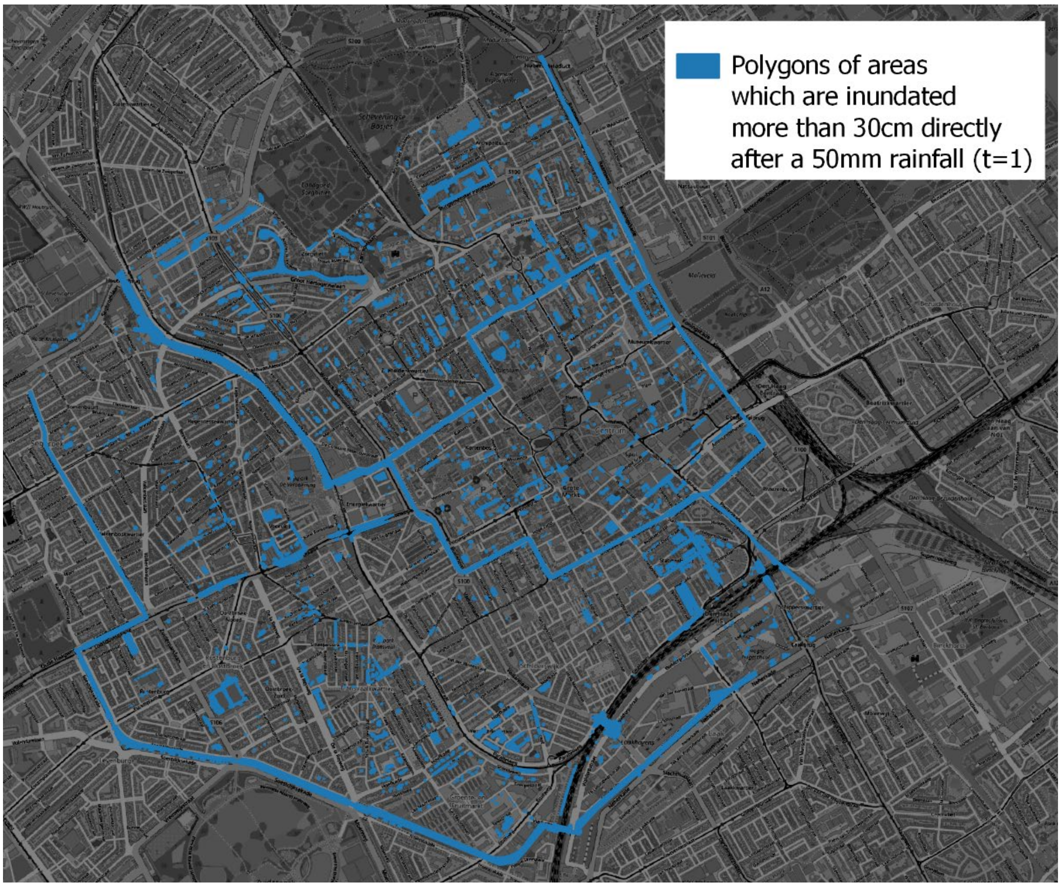

Figure 23: An example of the polygons representing inundated areas of over 30cm.

4.2.6 Step 2c spatial data of critical infrastructures

Spatial data about the four selected critical infrastructures are obtained through different sources, as listed in table 6. The layers were clipped with a polygon holding the case study area with the same form as the inundation maps. Figure 24 presents the spatial data of these four infrastructures.

Table 6 Selected critical infrastructures and their sources

Infrastructure	**Source**	Selected attributes
Road network	Previous CIrcle project, Open Street Map (Deltares, 2019)	Primary+link, secondary+link, tertiary+link, residential, cycleway, footway, living_street, pedestrian, service
Electricity stations	Stedin.net (open source)	Stations: low (7), middle(1), middle-low (493)
Hospital	Self-made layer	-
Supermarkets	Open Street Map	Shop: supermarket

The road network holds different types of roads. This means that at some roads multiple lines are drawn where in reality it is just one road (for example a street being both a residential street, a pedestrian road and a cycle path). Using a network like this gives more emphasis to roads which are used for multiple functions, thus can be regarded as more important. This has influence on the total amount of road segments flooded, but does not influence the number of people being affected by the flood.

Network operator Stedin has their data on location of cables and power boxes publicly available. The data on power boxes is divided in categories low, middle-low, middle and high voltage. The first three types are included in the analysis because these are the smaller boxes with thresholds of 30 centimetres.

The dataset of the supermarket contains 62 supermarkets, unevenly spread over the area. Possibly all types of supermarkets are included, ranging from very large ones to small grocery stores. This limits the validity of the dataset.

Figure 24: Spatial data of the selected critical infrastructures in the study area.

4.2.7 Step 3a disruption of networks

This section describes the workflows of how the disruption of the different infrastructures is spatially analysed per infrastructure type.

Road network

The disruption of the road network is analysed for all rainfall types, for all points in time. The outcome is the location and total length of inundated road segments (30 cm water depth).

1. The road network map + inundation polygons of all rainfalls, retrieved from the inundation maps, are loaded in QGIS
2. Using the clipper tool, the road segments are cut out which are inundated over 30cm. This is done for all rainfalls at all selected points in time.
3. Using the field calculator from the attribute table, the lengths of these segments are calculated.
4. In the 3Di model, the height of the bridges is not taken into account, it takes the ground level which is the height of the canal under the bridge. Bridges are unlikely to flood, thus these lengths will have to be subtracted. Using the waterways layer from Open Street Map, and a buffer of 10 meter around them, road segments which are

probably bridges are clipped. The total length of these bridge segments is also obtained using the field calculator (1911 meter).

5. The length of the bridge segments is subtracted from the length of the roads which are disrupted, for every rainfall type.

Electricity stations

It is assumed that once an electricity station is inundated over 30cm, it will cause a short circuit and it no longer works. It will have to be repaired manually. Hence, the electricity outage is analysed for all rainfalls at the point in time right after the rainfall. The outcome is a prediction where electricity shortage will occur.

1. Map of electricity stations + inundation polygons at t=1 (directly after the rain event) are loaded in QGIS. However, in this analysis the inundation polygons without buffer are used. A three meter buffer will give a large overestimation of the number of electricity boxes which will flood.
2. Using the research tool 'select by location' the electricity stations which touch, overlap or are within the inundation polygons are selected.
3. In the attribute table of the electricity stations a separate column is made, indicating whether or not the station gets flooded at a certain rain event (1 if yes, zero if not)
4. Using the QGIS tool 'TIN interpolation' an interpolation is made between all electricity stations for every rain event. The output is a raster file of the interpolation, with values between zero and 1.
5. This raster file is converted to a polygon using the 'Polygonize' tool. This creates a polygon around the flooded electricity stations, with a distance to another not-flooded electricity station of exactly half the length (see figure 25). Because most houses will be connected to the power box which is closest by, it can be assumed that this is the area where electricity outage is experienced. This method is validated with the risk analyst from Stedin.

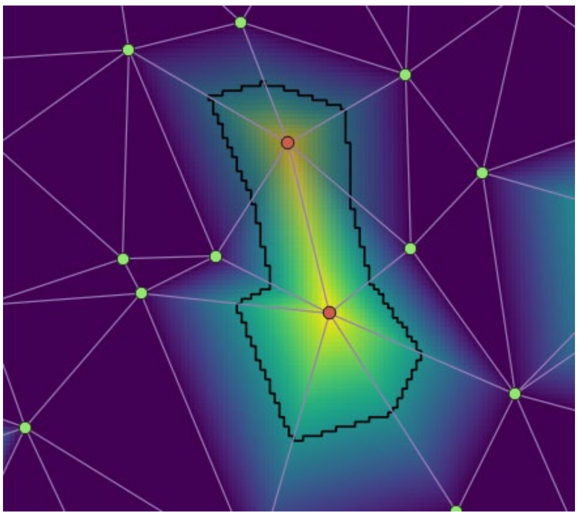

Figure 25: Detail of the polygon (in black) indicating areas experiencing electricity outage around flooded electricity stations (red dots).

Hospital HMC Westeinde

The direct effect of flooding to the hospital is analysed using the obtained inundation maps. The indirect effect of electricity outage on the hospital is analysed by spatially overlaying the electricity outage maps with a map of the hospital. The indirect effect of disruption of the road network to the hospital is analysed using network analysis. The follow procedure was followed:

1. The road network map + inundation polygons of all rainfalls are loaded in QGIS.
2. Using the 'difference' tool, the road network is constructed which is not flooded over 30cm.
3. Since bridges are not accurately present in the elevation map of the 3Di model, and are thus visualized as flooded, this is fixed manually. Three bridges close to the hospital are critical for the accessibility of the hospital, thus on these locations the roads are added manually. The locations are shown in figure 26.
4. Using the 'QNEAT3-Qgis Network Analysis Toolbox' and option 'Iso-Areas as Polygons (from Point)' the service area of the hospital is analysed for every rain event. The road network output of step 3 is used to create iso-areas around the location of the hospital which are reachable within 5 minutes with a speed of 15km per hour Also, an interpolation raster map is created to visualize the accessibility.

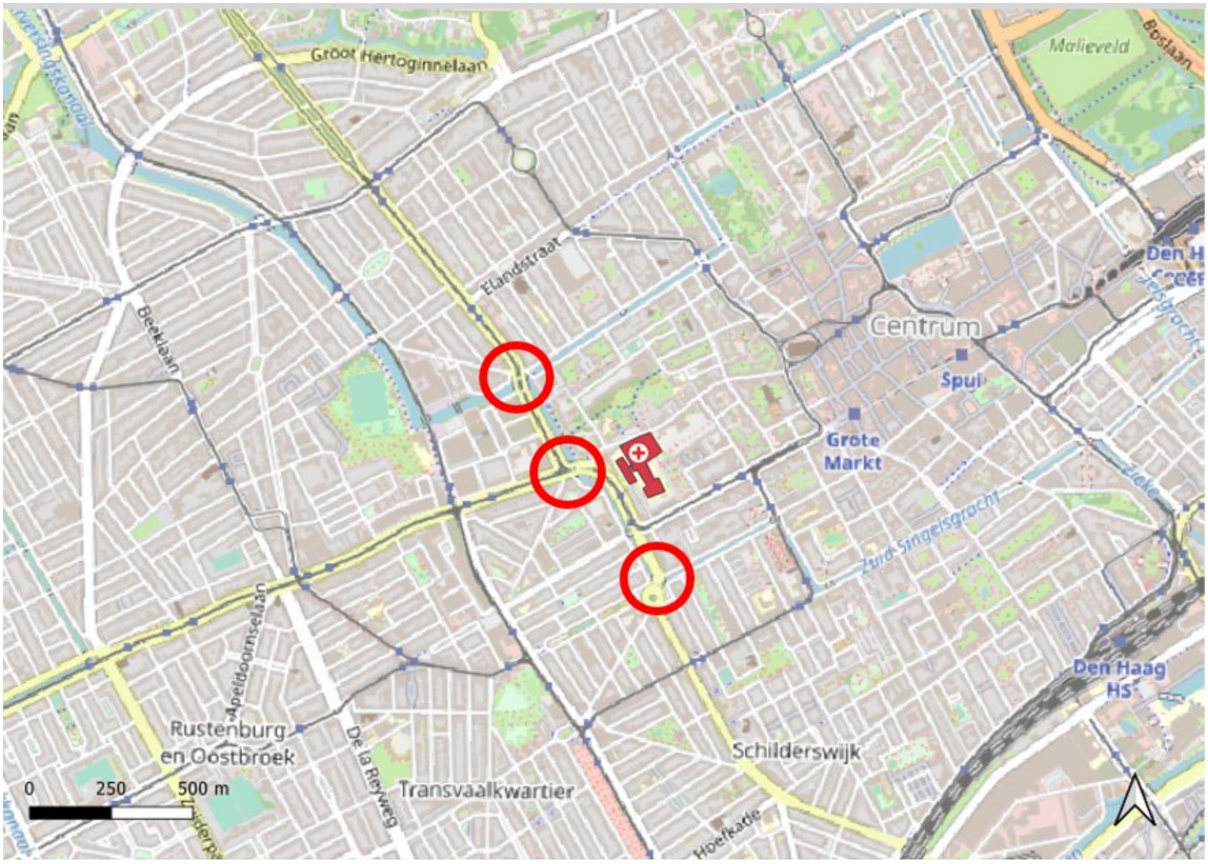

Figure 26: Locations of bridges which are important access roads to the hospital.

Supermarkets

Because the dataset of the supermarkets has its limitations, only one rainfall event is analysed with the sole purpose to show the method for assessing the vulnerability of supermarkets.

1. The layer of supermarkets and polygons of the inundated areas is loaded in QGIS.
2. The location of supermarkets are points. A buffer of 15 meter is created around the points to simulate a realistic surface area of these supermarkets.
3. Using the research tool 'select by location', the supermarkets which touch, overlap or are within the inundation polygons are selected.
4. Using the 'QNEAT3-Qgis Network Analysis Toolbox' and 'Iso-Areas as Polygons (from Layer)' the accessibility of the supermarkets is analysed. The chosen input layers are the supermarkets which are not flooded, and the road network which is not inundated (from step 3 of the hospital workflow). Polygons of five minutes walking distance from the supermarkets are created, as well as an interpolation raster map, to visualize the service area.

4.2.8 Step 3b CBS data, and disruption per inhabitant

In order to link the disruption of the networks to the number of people being affected by this disruption, data on population density in the city of The Hague is linked to the disruption maps. Statistics Netherlands offers data on population density with a level of detail of 100x100 meters (Statistics Netherlands, 2021). This is relatively coarse for the type of analysis done in this research. The data from 2020 is used and clipped to the study area of The Hague, as shown in figure 27.

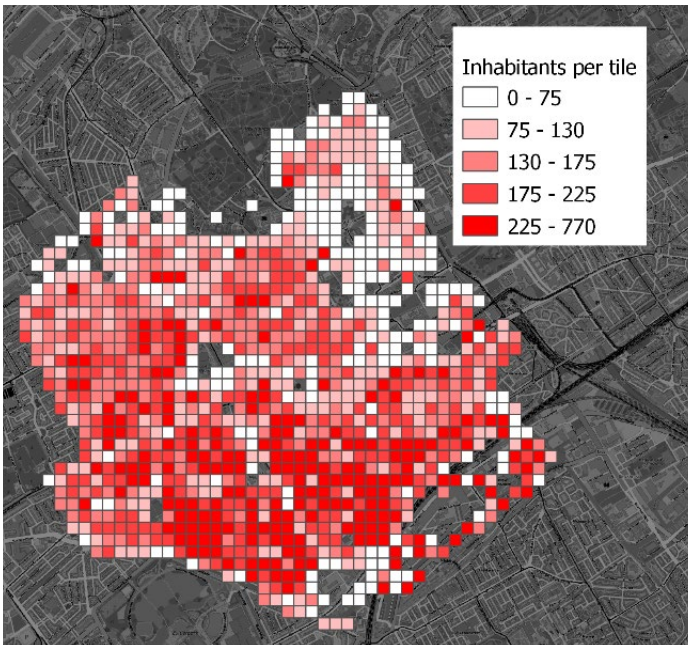

Figure 27: Population density in The Hague, per tile of 100x100 meters (Statistics Netherlands, 2021).

The direct impact per number of inhabitants of the floods on the road and electricity network is calculated using the research tool 'select by location', using the options *intersect, touch, overlap* or *are within*. For the road network, the features from the inhabitants data is compared with the flooded road segment maps (retrieved at step two of the road network disruption workflow). An example is shown in figure 28 for the road and electricity network after a 70mm rainfall. The selected tiles are exported as a separate layer, and in the attribute table the number of inhabitants are summed up using the field calculator. A downside of this method is that a flood of 30cm located at the outer edge of a 100x100 tile, will select the whole tile as 'affected'. A finer grid would give better estimations. Nevertheless one could argue that a flood of 30cm will still affect people in the surrounding of 100 meters around it, since it is realistic to say they will use the road segments further away from their homes as they go out. At the time of the rainfall event it will not be clear which roads are accessible and which are not. Thus a flooded road segment could lead to chaos in a wider area around it then only for people living next to that road segment who are not able to leave their house.

To estimate the number of people affected by electricity outage, the same procedure has been followed: the polygon layers of the different rain events for the predicted areas experiencing electricity outage are spatially compared with the raster of population density. Again, due to the coarse grid this is probably an overestimation. A finer grid will improve the estimations.

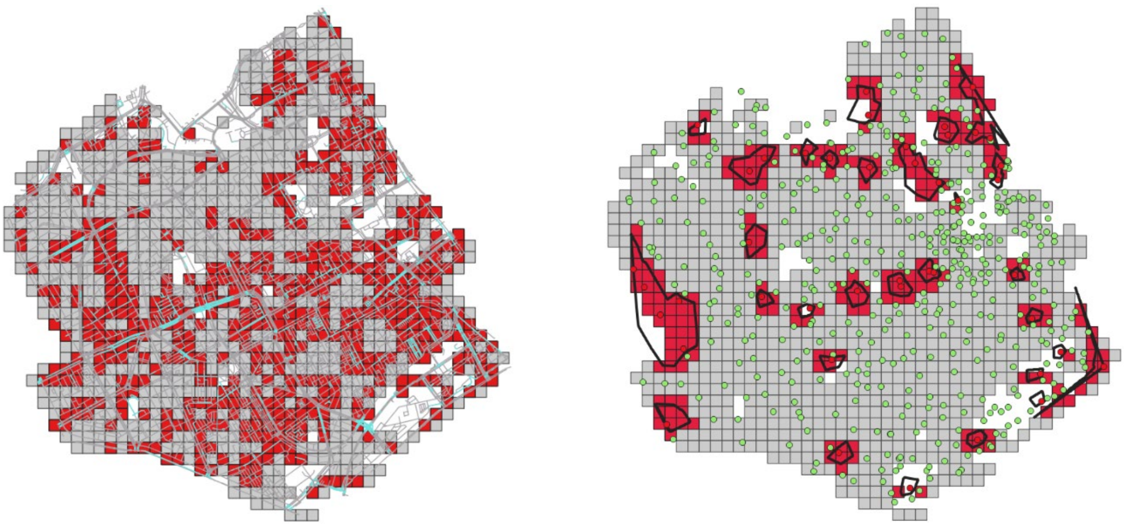

Figure 28: An example of the process of linking disruption of networks to the number of inhabitants affected.

4.3 Results

This section describes the results of the spatial analysis in QGIS of the inundation maps combined with spatial information on the infrastructure networks. First some of the inundation maps are shown, to have an overview of the consequences of the rain events. Then the direct impacts on the road and electricity networks are visualized and quantified to the number of people affected by the disruption. Lastly the direct and indirect effects (cascading effects) on the hospital HMC Westeinde and the supermarkets are visualized.

4.3.1 Inundation maps

The maps shown in figure 29a, b, c, d and e show the inundation right after the rainfalls of respectively 18.9mm, 35.7mm. 50mm, 70mm and 90mm. From these maps can be concluded that there are a few critical points in the study area which easily become flooded and will stay flooded for a longer period of time.

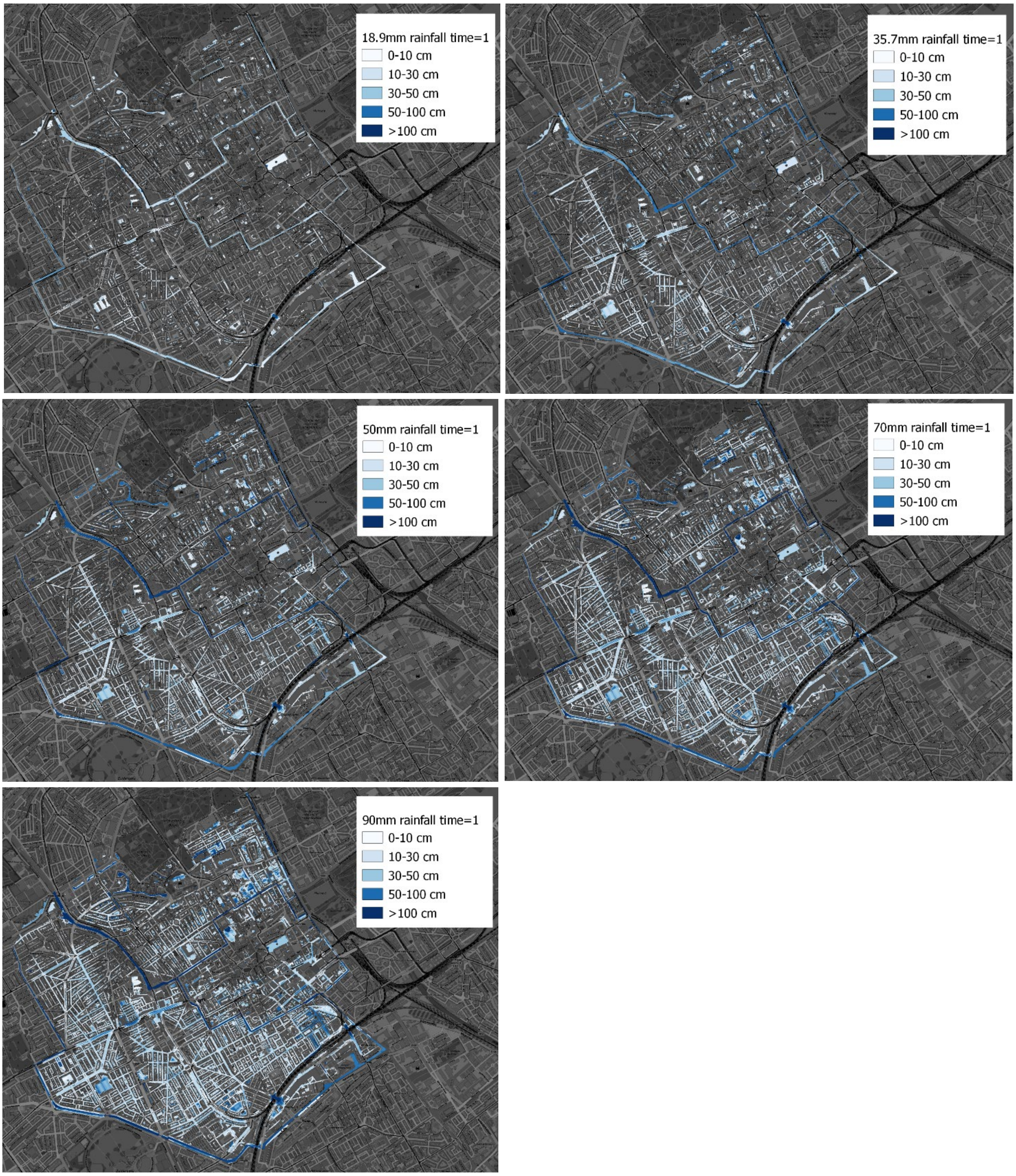

Figure 29a, b, c, d, e: Inundation maps retrieved from 3Di of 5 different rainfalls at the point in time directly after the rain event (time=1).

18.9mm rainfall (design 8)– recurrence time once in 2 years

A rainfall of 18.9mm in an hour (rainfall design 8) causes the least disruption, though three problem areas can yet be defined by studying this rainfall. Right after the event (time=1) the *Loosduinseweg* is flooded at some areas between 0-30 cm, but at some segments over 30 cm water remains on the street. Figure 30a shows the water depth over time at the crossing with the *Uitenhagestraat.* Water is predicted to stay on the road for about 1 hour.

The rail underpass *calandstraat* is severely flooded at time=1, at some locations around 100cm (see figure 30b). This is remarkable, because in the 3Di model an extra pump was installed at this location with an overcapacity of about five times the actual capacity. From figure 30b it can be concluded that after two hours (t=3) most water is pumped away. Though, due to the extra virtual pump it is uncertain if this is realistic.

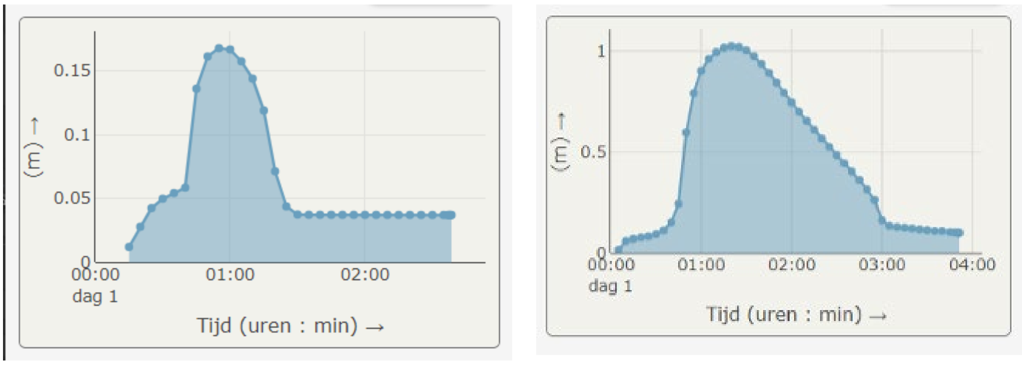

Figure 30 a, b: Water depth (meters) over time (hours:minutes) at the corssing Loosduinseweg (a) and Uitenhagenstraat and in the rail underpass calandstraat (b) after a rainfall of 18.9mm.

Another critical point is the rail underpass for trams at the *Leeghwaterplein*, which is flooded about 150 cm.

In general it can be concluded that with this severity of rain, which is predicted to have a recurrence time of once in two years, some areas in the city get flooded, but the duration is limited and it regards mainly tunnels. Within 3 hours after the event most water is drained.

35.7mm rainfall (design10) – recurrence time once in 10 years

Rainfall design 10 inundates larger areas in the city. Especially in the neighborhoods *Transvaal* and *Regentessekwartier* on a lot of roads water gets accumulated. The *Beeklaan* floods between 10-30 cm. The *Loonduinseweg* is flooded as well, at the lowest parts around 60cm. Though the duration of flooding on that location is limited, one hour after the end of the rainfall, the street is (almost) dry again (see figure 31a). The rail underpasses both at the *Calandlaan* and the *Prins Bernhardviaduct* get seriously flooded (over 100 cm) for longer periods of time (respectively 8 and 6 hours until all water is pumped out, see figure 31b and 31c). This takes into account the simulated overcapacity of pumps. Hence it can be concluded that in reality this will take longer. Six hours after the rain event, most water has left the model, thus the simulation was stopped at that point.

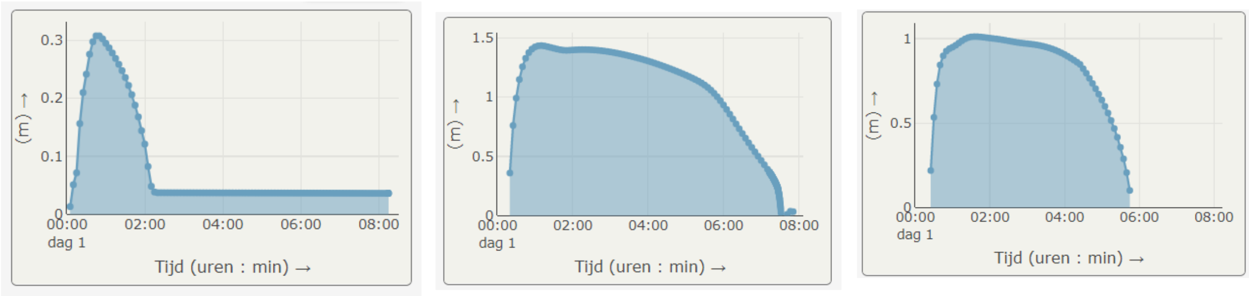

Figure 31a, b, c: Water depth (meters) over time (hours:minutes) at the location Loonduinseweg (a) *, rail underpass Calandlaan (b) and railunderpass Prins Bernhardtviaduct (c) after a rainfall of 35.9mm.*

50mm rainfall – recurrence time once in 50 years

Again more parts of the study area are inundated. Now also roads along the canals get inundated. For example along the *Zuid West Singelsgracht* on some parts 10-30cm water accumulates. This creates dangerous situations because it can become unclear how to distinguish the road from the canal. This risk starts at an inundation of 5 cm along the canal (Deltares, 2019). Also in the area on the north side of the train station *Den Haag HS* water accumulates, resulting in 30-50 cm of water on the *Stationsweg* and surrounding roads. As expected again the previously mentioned rail underpasses flood more severely and for longer durations. Since the duration depends heavily on the capacity of pumps it is difficult to say what the duration of disruption to those critical points will be. The 3Di software estimates disruptions of over 12 hours. The *Loosduinseweg* is free from water after 2 hours after the rain event.

70 and 90 mm rainfall – recurrence time once every 200 and 500 years

These scenarios are rather extreme. Directly after the rainfall most streets have accumulated about 10-20 cm of water. The *loosduinseweg* is inundated about 50-80 cm on some parts, which takes between 5-10 hours to vanish completely. For the 70mm rainfall the threshold of 30 cm is breached for large parts of that road on between 1 and 3 hours. For the 90mm event this can take between 3 and 6 hours for some segments. For both events the area on the north side of the train station *Den Haag HS* as well as the previously mentioned rail underpasses are severely flooded at the end of the simulation, 12 hours after the rain event. It is unclear how long it takes for the water to be pumped away for these type of rains.

4.3.2 Road network

Direct effects of flooding to the road network

The rainfall has a direct impact on the functioning of the street network in The Hague. The different types of rain events influence the amount of water on the streets (water depth), the length of the segments flooded (as a percentage of the total length), and the duration these segments are flooded. A threshold of 30 cm inundation on the road is chosen after which a road is not usable anymore for cars, trucks, ambulances or the police. Using this threshold value, the disruption is visualized in maps (figure 32 and 33). Also, the disruption is quantified to the percentage road segment flooded, and the number of people on which this flood has an impact.

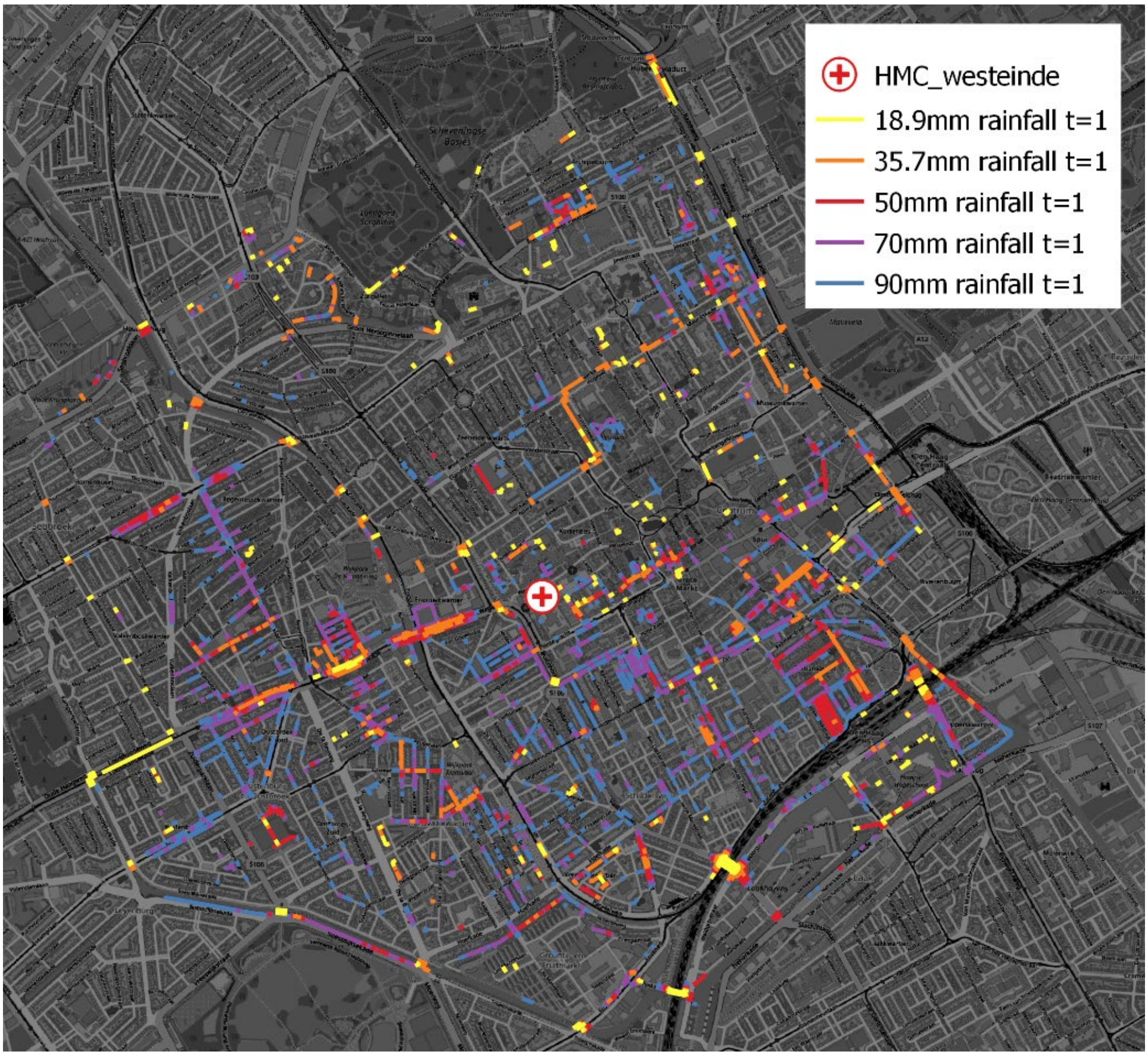

Figure 32: Road segments inundated at least 30 cm directly after the rainfall (t=1). Different colours indicate the different rainfalls simulated in 3Di.

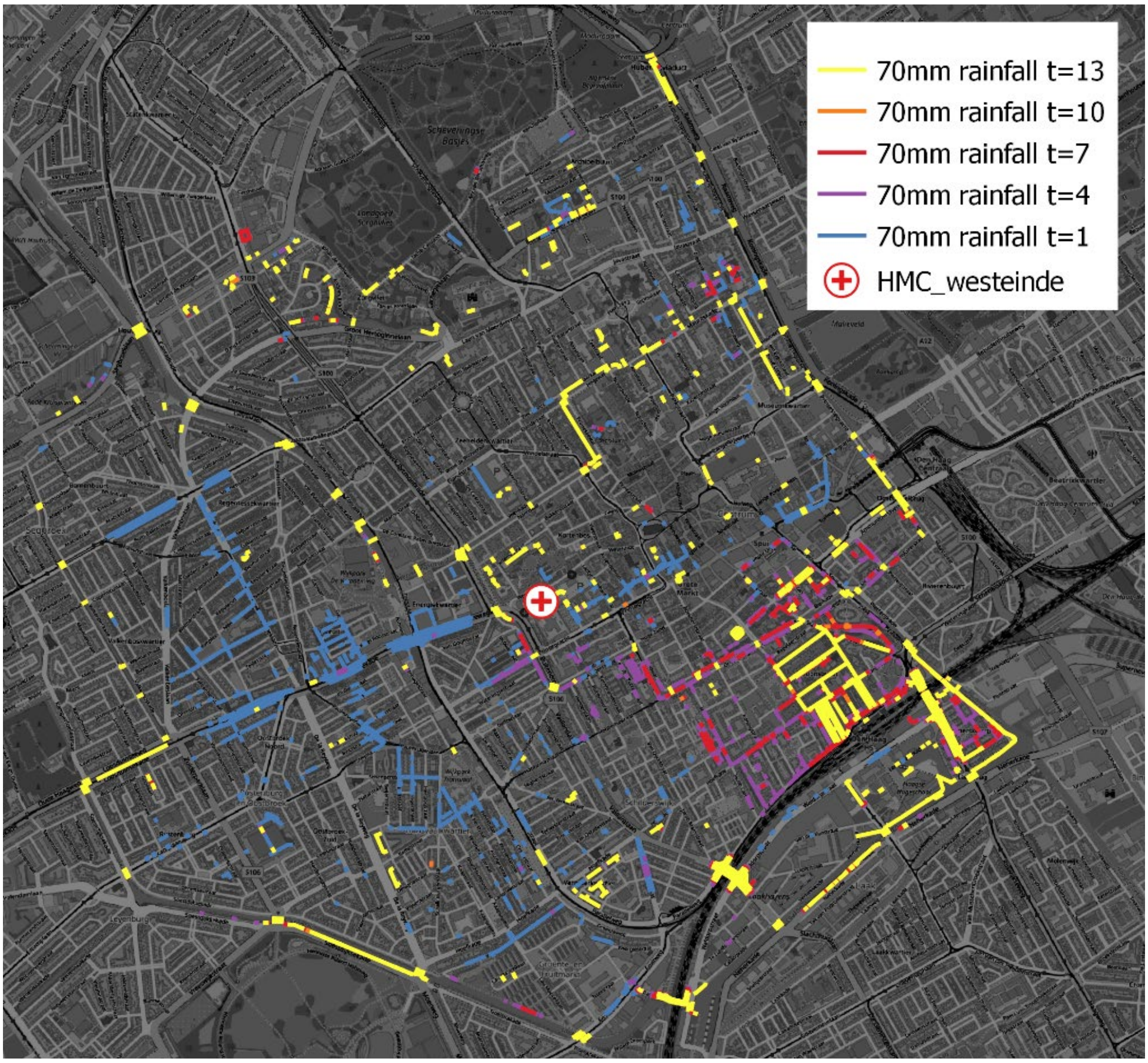

Figure 33: Road segments inundated at least 30 cm after a rainfall of 70mm in one hour.

Figure 32 and 33 indicate clearly the problem areas which were also indicated by studying the inundation maps. The *Loosduinseweg* and the rail underpasses *Calandlaan* and *Prins Bernhardviaduct* inundate with low intensity rains. Though, water on the *Loonduinsweg* can leave the road within a reasonable time. The area north of the train station Den Haag HS is a problematic area with possible high water levels for relatively long durations.

Quantification of disruption road network

Table 7 shows the length of road segments flooded per type of rainfall at each point in time. The total length of road segments in the study area is 468,010 meters, which enables the results to be converted in a percentage of road network disruption in the study area. Simulations of rainfall design 8 was stopped after t=4 because it seemed that all water disappeared from the model. Hence, the disrupted road segment is estimated to be 0. The same holds for rainfall design 10 after time step t=10. For the 50mm, 70mm and 90mm rainfall, the water never completely left the models after the simulations ended.

For the relevant points in time the number of people being affected by the road network disruption are calculated, which are also presented in table 7. In total there are 176,325 inhabitants in the study area, which allows for conversion to percentages.

Table 7: An overview of the disruption per rainfall event of the road network in length of segments and in number of people affected.

Type of rainfall (mm per hour)	Point in time (in hours)	Length of road segments inundated over 30cm (m)	Percentage of road inundated in the study area	Number of people affected by the disruption	Percentage of people affected by the disruption in study area
90 mm					
	1	64,704	13.8%	106670	60.5%
	4	54,739	11.7%		
	7	43,264	9.2%		
	10	32,238	6.9%		
	13	24,403	5.2%	41120	23.3%
70mm					
	1	39,210	8.4%	81715	46.3%
	4	30,141	6.4%		
	7	22,945	4.9%		
	10	17,351	3.7%		
	13	16,784	3.6%	34980	19.8%
50mm					
	1	20,882	4.5%	53470	30.3%
	4	16,138	3.4%		
	7	11,068	2.4%		
	10	8,305	1.8%	29025	16.5%
35.7 mm					
	1	12,237	2.6%	41330	23.4%
	4	8,278	1.8%		
	7	2,767	0.6%	22010	12.5%
	10	estimated to be 0	0.0%		0.0%
19.8mm					
	1	2,518	0.5%	18330	10.4%
	4	estimated to be 0	0.0%		0.0%

These results are plotted in figure 34. The trendlines are downward sloping following a rather linear trend up until t=10. The lines of the different rainfall event are relatively parallel to each other, meaning the slopes are about the same thus the disruption diminishes with the same rate for all rainfalls over time.

To convert the road segments of the road network flooded to the number of people affected by it, the datapoints at the beginning and ending of the lines are taken.

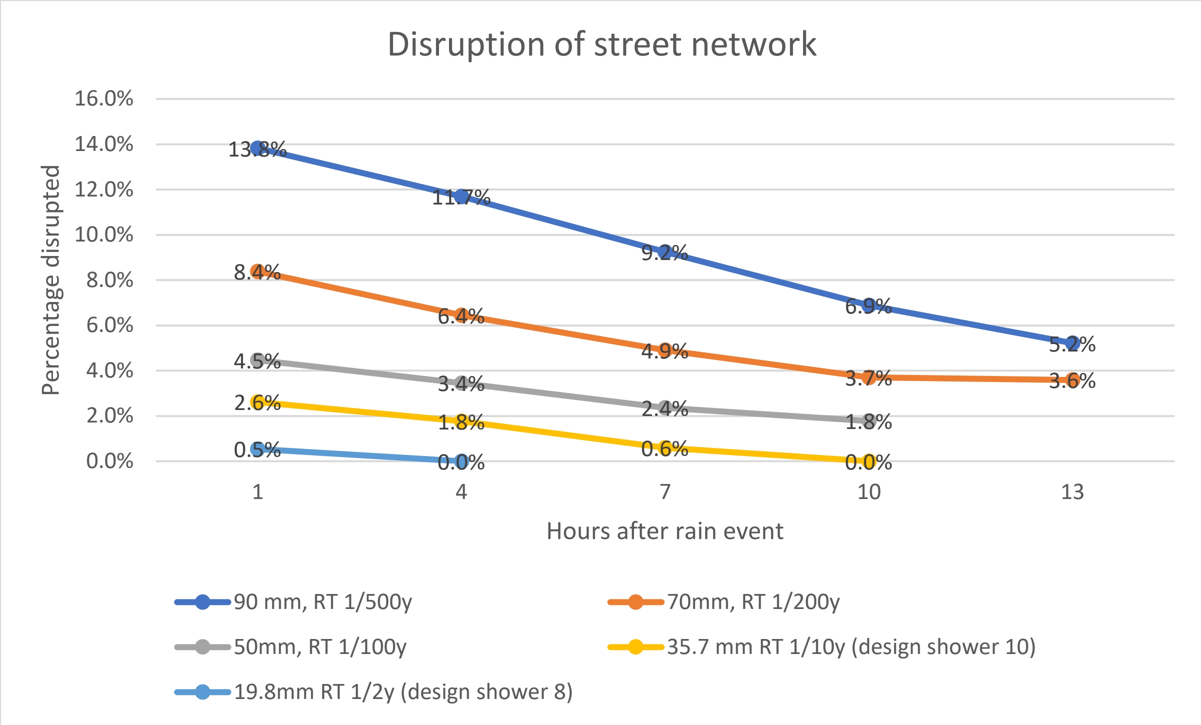

Figure 34: Percentages of road segments flooded per rainfall event.

When comparing the road network disruption in terms of road segment length and number of people disrupted, a jump in impact can be observed. Whereas the range of disrupted road segments directly after the rainfall lies between 0.5% (2,518 km) and 13.8% (64,704 km), the number of people affected by the disruption range lies between 10.4% (18,330 people) and 60.5% (106,670 people). Note that the jump in impact is mainly explicable by the way *affected by road disruption* is defined. In this research every person who lives within the 100mx100m tile where a road segment is flooded over 30 cm is classified as *affected*. It is assumed that if a section of the road is impassable this has consequences for a wider area. Next to that, the jump in impact can also be explained by the fact that population density in the south of the study area is higher. This is also the area where most of the roads get flooded.

Using the number of people who are predicted to be affected by the road network disruption at different times (as presented in table 7), the resilience triangles could be established for each rainfall event. These are presented in figure 35. The y-axis presents the number of people who are not affected by the disruption of the road network in the study area. As shown in the literature review, the area under the resilience triangles represent the resilience of the system. This resilience differs for each rainfall event.

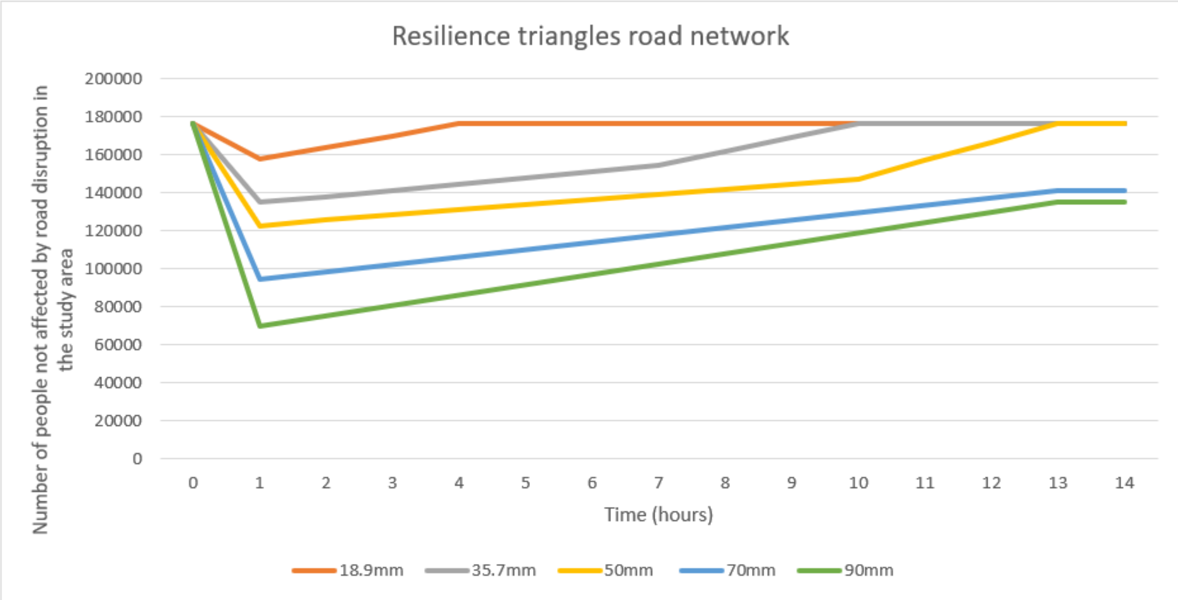

Figure 35: Resilience triangles of the road network for different rainfalls.

Validation of results Road network:

The results of the analysis are validated in an interview with an expert from the municipality of The Hague from the department of sewerage soil and roads. The full transcript of the interview is presented in Appendix D.

The vulnerable areas of the city are accurately pointed out by the analysis. However the scenarios seem slightly extreme. Probably the results of the 18.9mm event are more applicable once every 10 years instead of once every 2 years. In the past 10 years some tunnels got flooded, though most of them got new pumps now which reduces the chances of flooding. The estimates of the number of people affected by the disruption could be correct. However the question remains whether 'affected' is the right terminology. Because, during a rain people will tend to stay inside anyways. Only people who need to go outside and cannot because of the disruption will actually be affected. This is not incorporated in the estimation. The municipality uses a norm of maximum inundation to decide whether or not to improve the resilience of the road network. If water stays on the road for longer than 45 minutes after a rainfall expected to happen once every 2 years (18.9mm), the system should be improved. Typical measures to reduce the inundation are threefold: 1) improve the sewage system (increase capacity of pumps and pipes) ; 2) increase infiltration (installing specific crates, using the tram track for infiltration, lowering green areas and increase amount of greenery in general); 3) on the lowest scale placement of sills or physical thresholds to refrain water from flowing to certain vulnerable areas (cellars or tunnels).

4.3.3 Electricity network

Direct effects of flooding to the electricity network

If an electricity station is inundated with 30cm water or more, there is a large chance it will cause electricity outage. The location of these electricity stations is hence crucial. For all rainfalls is analysed how many and which stations are disrupted, and which areas could face electricity outage. This can be visualized using an interpolation raster, as shown in figure 25 in the methodology section. The interpolation raster shows the relative distances between stations which are flooded (1) and which are not flooded (0). It is assumed that between value 0 and 0.5, the electricity will be provided by the power station which is not flooded, due to redundancy in the network. The results of the analysis of the study area is presented in figure 26. There are six areas which are predicted to experience electricity outage due to flooding. The figure shows which type of rainfall event will inundate the power box in that area. The lightest rainfall (18.9mm) will inundate only one box, the heaviest (90mm) all six.

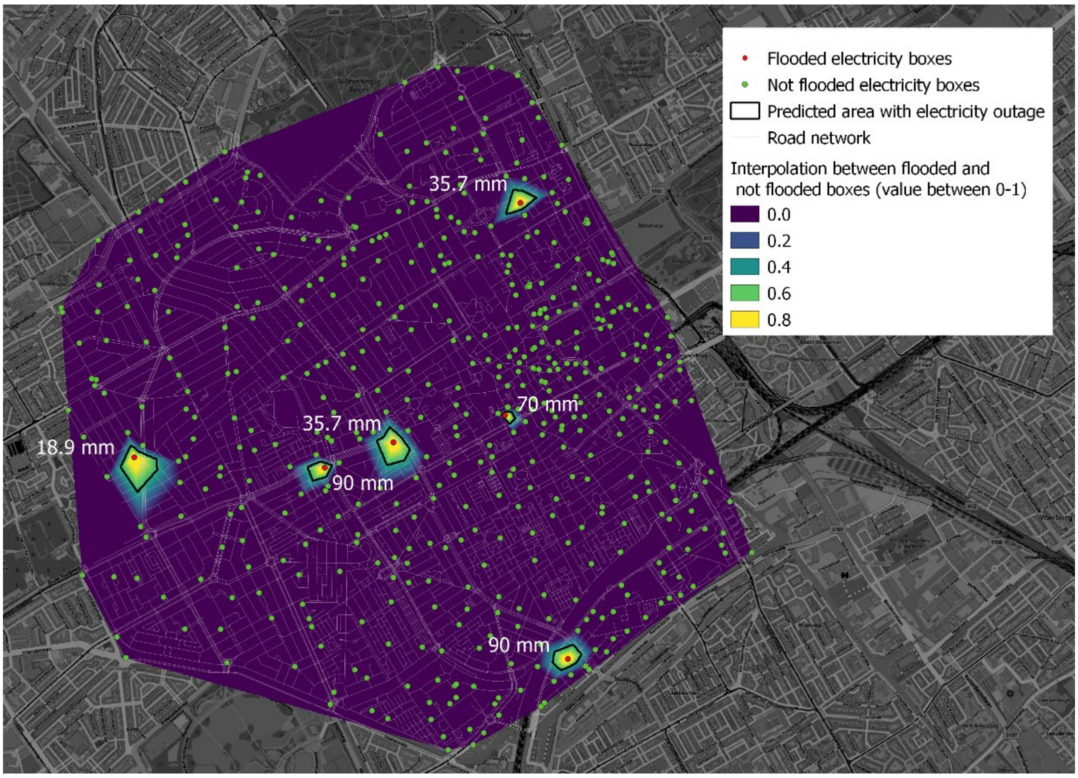

Figure 36: predicted electricity outage in the study area.

Quantification of disruption of the electricity network

In total there are 501 power boxes in the study area. For both the rainfalls of 35.7mm and 50mm the same power boxes are inundated over 30cm (the same amount at the same locations). Once an electricity box fails, it needs to be repaired manually by the network operator. As soon as the location is accessible after the flood, mechanics will install a generator to provide immediate electricity to the homes. This takes on average 3 hours. For each rainfall an estimation is made what the duration is until the location of the power box is accessible to mechanics. This estimation is based on the results of the road network disruption maps and by comparing it to a previous rainfall event in Copenhagen. This was an extreme event (150mm in 2 hours). There it took about 5 hours until mechanics could start repairing the electricity network (Danish Emergency Management Agency, 2012). Table 8 presents an overview of the amount of power boxes flooded in the study area, the number of people affected by the outage and the estimation of the duration until restoration can start.

Table 8: An overview of the disruption per rainfall event of electricity network and in number of people affected.

Rainfall events	Number of flooded power boxes	Percentage of flooded power boxes in the study area	Number of people living in the area with predicted electricity outage	Percentage of people living in the areas with predicted electricity outage in the study area	Hours until restoration starts
18.9 mm (rainfall design 8)	1	0.2%	808	0.46%	0
35.7 mm (rainfall design 10)	3	0.6%	1733	0.98%	1
50mm	3	0.6%	1733	0.98%	2
70mm	4	0.8%	1850	1.05%	2
90mm	6	1.2%	2738	1.55%	3

It can be concluded that depending on the rainfall, between 808 and 2738 people will experience electricity outage which is a percentage range of 0.46% and 1.55%. The resilience triangles can be established using the estimated time until restoration can start and the average amount until the electricity box is replaced by a generator. These are presented in figure 37. Appendix F presents the table with the number of people experiencing disruption over time.

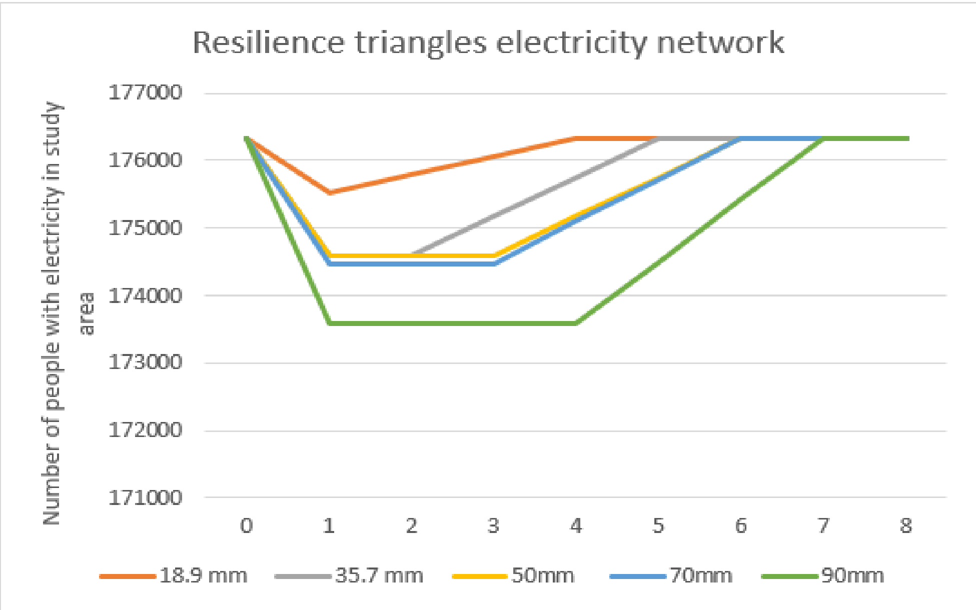

Figure 37: Resilience triangles of the electricity network for different rainfalls.

Validation of results Electricity network

The results of the analysis of the electricity network are validated in an interview with the risk analyst of network operator Stedin. The full transcript of the interview are presented in Appendix E.

In general the risk analyst believes the method to evaluate the number of people affected by electricity outage is an effective and appropriate one. However speaking from experience of the past five years he has not seen any electricity outage due to flooding in the area. Hence he questions if the location of the boxes are accurately placed in the model. The threshold of 30 cm is used by the network operator as well. The network operator estimates the risk of electricity outage due to flooding relatively low. Stedin uses a form of a risk matrix (as explained in the literature review) to evaluate whether or not to invest in measures. The risk of flooding is estimated to be low with a low impact on people. There is a law describing the amount of financial compensation a customer is entitled to after certain duration of electricity outage. Typical measures to decrease the chance of electricity outage due to flooding is to relocate the electricity box to a higher area. Another option is to raise the box with a specific frame 60 cm from the ground. This is sometimes done with boxes located near a waterfront. However this is only considered viable if the boxes need to be replaced anyway.

4.3.4 Hospital service

The consequences of a heavy rainfall for the hospital HMC Westeinde can be direct, through flooding of the hospital area, or indirect, through disruption of the road or electricity network. First the results of the direct effect is presented, and then the two cascading effects.

Direct effect of flooding

When studying the inundation maps of the hospital area, presented in figure 38a, 38b and 38c, the risk of flooding seems small. The dark blue line visible on the maps is the canal. For the 35.7mm rainfall there is a maximum of 5 cm water around the hospital area. This does not change much when comparing it to the 50mm rainfall. The inundation map of the 90mm rainfall shows some water depth of 30cm on the streets at the northside of the hospital. But still, there is no water on the edges of the building, indicating that the water is not likely to enter the building or its cellar. It can be concluded that the direct impact of flooding to the hospital is small.

Figure 38 a, b, c: Details of the inundation maps of the area around HMC Westeinde for a rainfall of 35.7mm (a) 50mm (b) and 90mm (c).

Indirect effect of road network disruption to hospital service

The first cascading effect, the impact of the disrupted road network on the hospital, can be visualized using network analysis. Figure 39 shows the service area of the hospital, meaning the area which is reachable from the hospital within 5 minutes (first red line from inside out) and 10 minutes (second line with same colour from inside out) using the road network with a speed of 15 km/hour. As explained in the methodology section this can be taken as the average speed through the city. The green line shows the service area of the road network which is not disrupted. The blue line shows the service area after a rainfall event of 35.7mm. As expected the area became smaller, because not all roads can be used. For the 50mm rainfall the area becomes again smaller. It must be noted that the speed is set constant at 15km/hour, which is not realistic when comparing normal conditions to post-flood conditions. Travel speeds will be lower after a flood, which increases the difference in service areas even more.

Figure 39: Visualization of reduced service area due to road network disruption.

Differences in reachability can also be visualized using interpolation. It then becomes clear which routes are important access roads. This is visualized for the normal situation (figure 40), a 35.7mm rainfall (figure 41), a 50mm rainfall (figure 42) and the 90 mm rainfall (figure 43). Looking at the 50mm rainfall event it becomes clear the southern part of the area becomes very hard to reach. In other words: for the inhabitants in that area it will become difficult to access the hospital. In the situation of the 90mm rainfall the southern area became an island: the roads in that area are not connecting to the roads in the centre. Inhabitants of that area cannot access the hospital using the roads in this model.

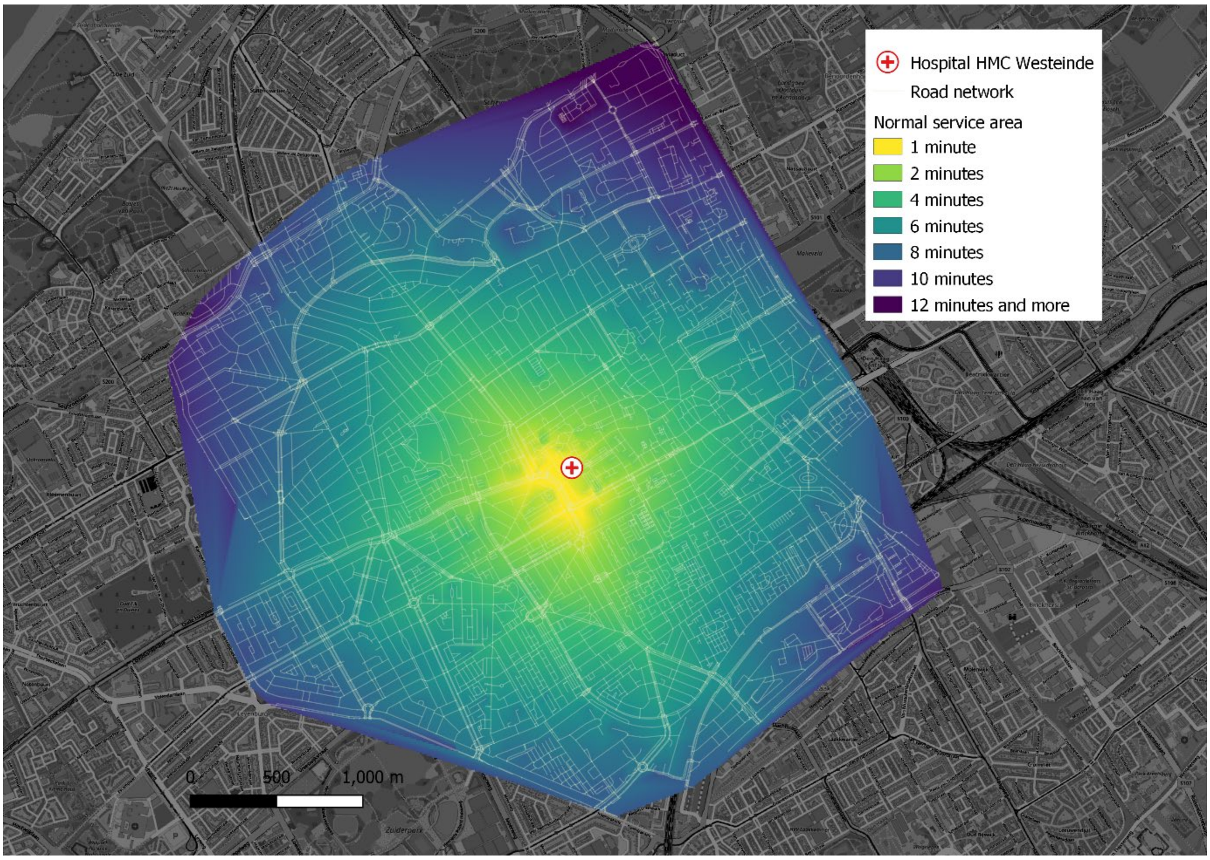

Figure 40: Visualization of reachability of the hospital using interpolation, normal situation.

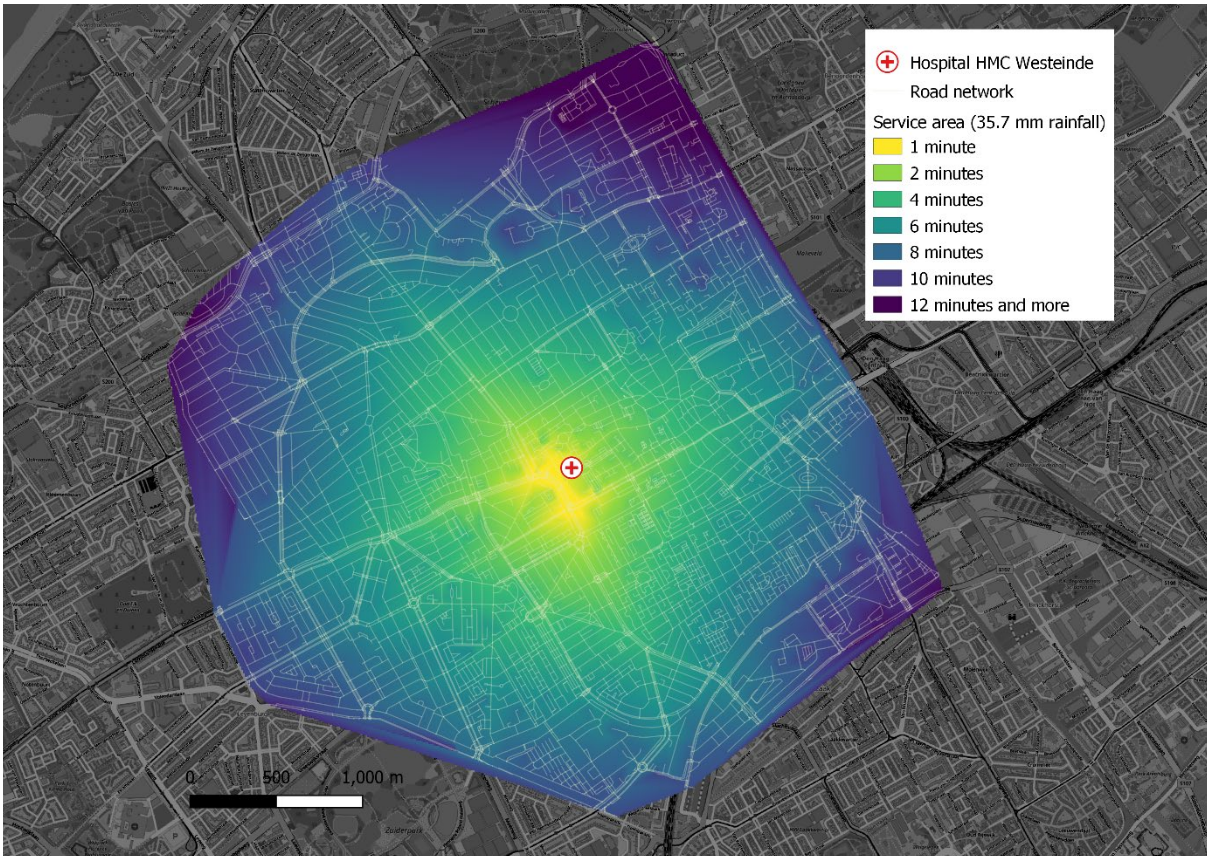

Figure 41: Visualization of reachability of the hospital using interpolation after 35.7mm rainfall.

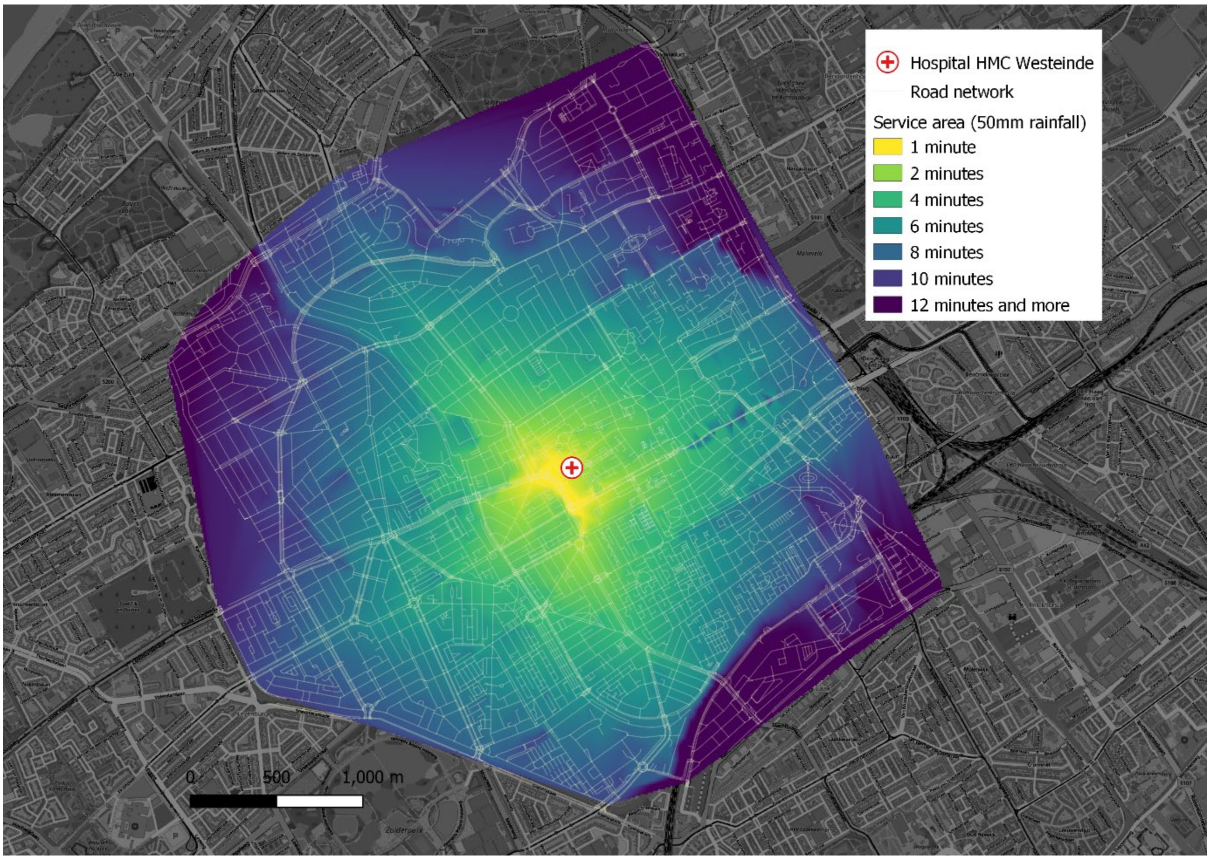

Figure 42: Visualization of reachability of the hospital using interpolation after 50mm rainfall.

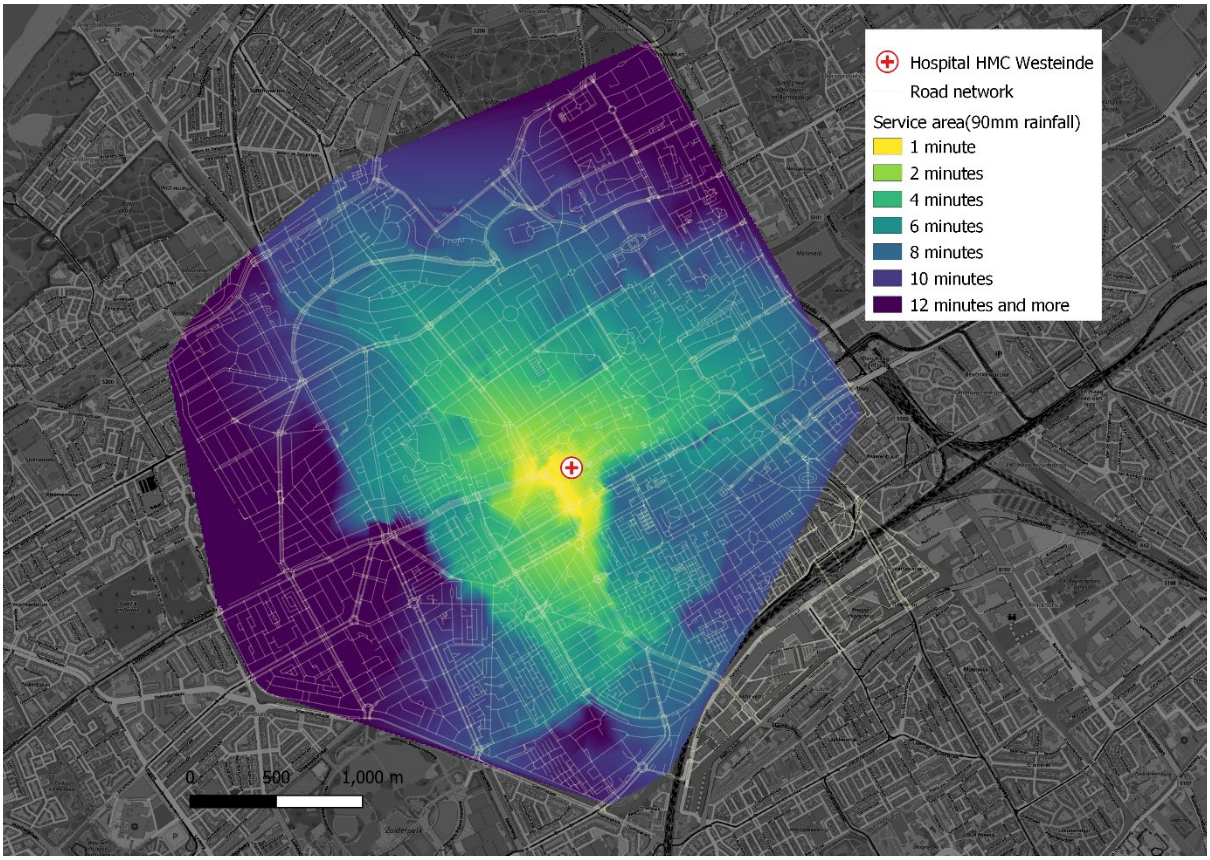

Figure 43: Visualization of reachability of the hospital using interpolation after 90mm rainfall.

Indirect effect of electricity network disruption to hospital service

To analyse whether the second cascading effect, electricity outage, has influence on the Hospital HMC Westeinde, the electricity outage map is used. An overlay with the predicted areas of electricity outage after a 90mm rainfall is used and presented in figure 44. It shows that even the most extreme rainfall event is not likely to cause electricity outage to the hospital.

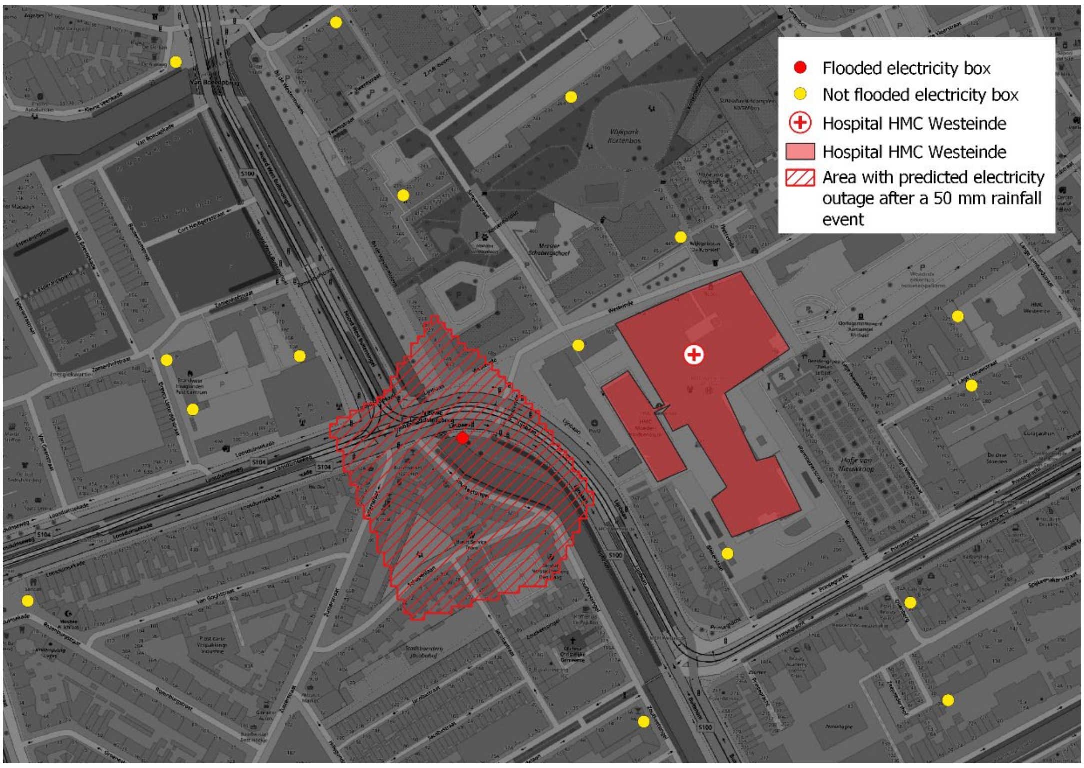

Figure 44: Map of the area around the hospital with predicted electricity outage.

4.3.5 Supermarket disruption

This section presents the results of a method how the direct and indirect effects of heavy rains could be analysed. However, due to an unreliable dataset of supermarkets, the analysis has not been carried out in detail. Only the consequences of a 50mm rainfall is studied. The direct effects are flooding of the supermarkets. The cascading impacts are the reduced accessibility of the street network and electricity loss.

Direct and indirect effect of flooding to supermarket accessibility

By creating an overlay map of the inundated areas with more than 30cm water on the streets and the location of the supermarkets, a prediction is made which supermarkets will be flooded. In total there are 62 supermarkets in the area of which 5 are predicted to experience flooding and will have to close because of that (8.1%). These are shown in figure 45 as blue dots.

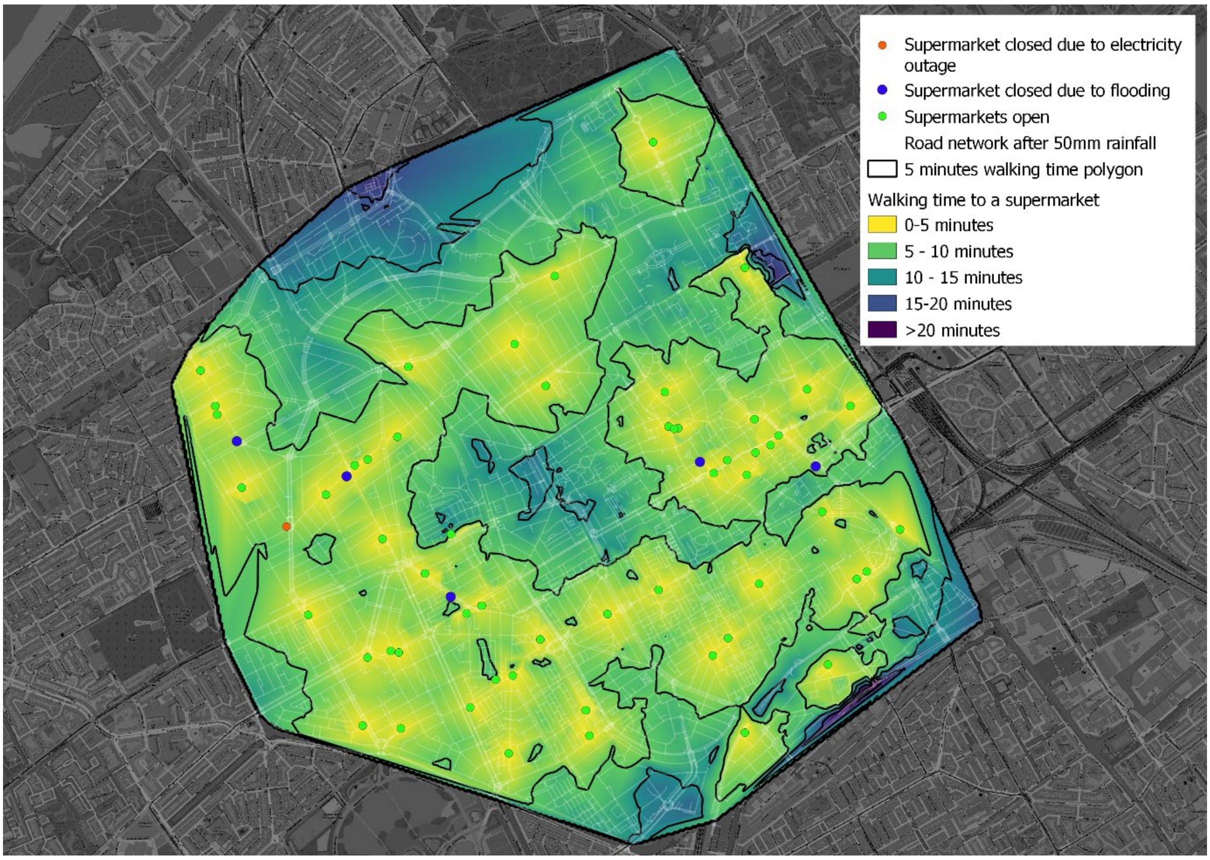

Figure 45: Service area of supermarkets and grocery stores after a 50mm rainfall.

In the same way an overlay with the predicted areas for electricity outage and the supermarkets is made. This results in 1 possible supermarket which is predicted to experience electricity loss as presented in figure 45 as an orange dot.

Thus 6 out of 62 supermarkets will face disruption due to the rainfall (11.3%). To assess the consequences to the accessibility of the supermarkets to the inhabitants, the same approach is used as how the hospital's accessibility was evaluated. However, for this analysis the service area of multiple points in one layer are calculated. The speed is set at 5km/hour (walking speed) and for every five minutes walking distance from a supermarket, a polygon is drawn. The results are also presented in figure 45.

Looking at figure 45, a few dark blue areas can be identified from where it takes over 10 minutes by foot to reach a supermarket. The areas at the edges at the North and East are parks thus it makes sense that there are no supermarkets around. The blue area in the middle is an area without access to supermarkets and grocery stores within 10 minutes. However, this is not due to flooding or electricity outage, because there are no open supermarkets in the area either. Furthermore, the supermarkets which have to close are located in areas within the 5 minute service areas of other supermarkets. There is a redundancy of supermarkets. Hence, it can be concluded that the influence of a 50mm rainfall has limited effects on the accessibility of supermarkets. Inhabitants will still be able to do their groceries. Though it should be noted that the dataset is probably not representative, thus this section merely presents a methodology rather than definitive results.

4.4 Conclusion

This chapter describes how the disruption of different critical infrastructures due to flooding as a result of heavy rainfall can be mapped and quantified. 3Di software is used to assess the inundation as a result of different types of rainfalls. The inundation maps are compared with spatial data of the critical infrastructures to define locations and amount of disruption in QGIS. The main conclusions are summarized below.

4..4.1 Direct effects to the road and electricity network

A rainfall of 18.9mm in one hour (rainfall design 8), predicted to happen once every two years, results in moderate flooding in the study area. Mainly tunnels will get inundated and disrupt the traffic. Three hours after the rainfall, almost all water is drained and the disruption is over. 10.4% of the inhabitants (18,330 people) in the study area will be affected by road disruption for about one hour. It is expected that 0.46% of the inhabitants (808 people) might face electricity outage. The power grid is predicted to be back in service after 3 hours after the rainfall.

A rainfall of 35.7 mm (rainfall design 10), predicted to happen once every 10 years will cause more inundation in the study area. The tunnels will inundate for a longer time and there is more water on the streets for a longer duration. After roughly six hours most water is drained. 23.4% of the inhabitants (41,330 people) will be affected by the road network disruption for one hour, and 12.5% (22,010 people) for at least three hours. 0.98% of the population might experience electricity outage (1733 people).

4.4.3 Effects to the mobile network

Analysis of the direct and indirect effects of flooding due to heavy rainfall found that the mobile network is not vulnerable to this hazard. The antennas are mostly located high enough to withstand flooding, and consequences of electricity outage are limited. Furthermore there is a high redundancy of antennas in the mobile network.

4.4.3 Effects to the hospital HMC Westeinde

It is not likely that the hospital HMC Westeinde will be directly affected by heavy rain in terms of flooding of the buildings or the direct surrounding. Even after a very extreme rainfall (90mm), it is not likely that the water will enter the building or the cellars. Also, the hospital is not located in an area with expected electricity outage for all simulated rainfalls. Though the accessibility of the hospital is reduced by the cascading effect of flooding on the road network. Using network analyses the reduction of service area was visualized

4.4.4 Effects to the accessibility of hospitals

The consequences of a 50mm rainfall (with a recurrence time of once every 50 years) to the accessibility of the supermarkets to the inhabitants of the study area is limited. It is expected that 6 out of 62 supermarkets (11.3%) might have to close due to electricity loss or flooding. One of the supermarkets is located in an area which seems critical, and this results in significant longer travel distances to a supermarket for the people living in that area.

4.5 Discussion and recommendations

To evaluate the validity of the conclusions, it is important to take into account the limitations to the methodology.

4.5.1 3Di simulations

Firstly, the inundations maps are based on simulations of rainfalls in a virtual model of the study area. The model is very detailed to approach reality as good as possible, but it still has its limitations. Most importantly, the virtual model only describes a relatively small area which lead to problems at the model boundaries. As described in the methodology section, the boundaries are modelled as 'closed', resulting in a lot of water accumulating at the lowest points in the model. To improve the validity four virtual pumps were added. It is clear that the capacity of the pumps influences the duration of flooding in the model. Hence, for extreme rainfalls the model simulations were ended after 13 hours. It is very hard to be sure about the duration of flooding for the heavy rainfalls, other than that it is most certainly an underestimation.

A second limitation to the simulations is that bridges are not correctly represented in the digital elevation model, which lead to a predicted flood of bridges which are most certainly unrealistic. Mainly the estimates for the accessibility of the hospital and the supermarkets were affected by this limitation.

Next to that, the virtual model is based on a lot of assumptions which are very important for the predictions. For example, the coefficients about infiltration and friction are estimates, because that depends on so many local characteristics. Also the sewage system is based on input of the municipality about the locations of the pipes, but does not hold the exact dimensions. To predict whether or not water will flow from one street to another is very hard. Sometimes a small bump in the road of only 10 cm can make a lot of difference. Thus, the results of the 3Di simulations should always be validated by experts who know the physical situation. Concluding, the 3Di simulations make it possible to indicate problem areas and assess likely effects of flooding, but are never to be trusted on their own without expert judgement.

It is recommended that for a better analysis a larger study area is taken. Simulations will take longer, but results will be more reliable. More attention should be payed to estimating the drainage capacity at the boundaries of the model especially if canals intersect with the model boundaries. This will mainly increase the validity of the duration of the disruption. Also, the pumps at the rail underpasses have to be incorporated correctly in the model. Lastly it is recommended to use a digital elevation map with the correct representation of bridges in the 3Di model.

4.5.2 Quantification road network disruption

As mentioned, the missing bridges in the digital elevation map have an influence on the estimation of the disruption to the road network. Next to that, it is known that roads along a canal which are inundated 5 cm yet create unsafe situations because it becomes unclear where the road ends and when the canal starts (Deltares, 2019). This difference in threshold to whether a road becomes inaccessible or not is not taken into account, which would be a good addition.

Furthermore, it would be interesting to assess the road network disruption including the importance of the roads. This is now incorporated slightly by using multiple types of roads in the road network, ensuring that roads with more purposes have multiple lines. Though, this could be improved by carrying out a network analysis including population densities, origin and destination data of travellers and important locations.

Lastly the estimate how many people in the end will be affected by the road disruption is an approximation which could be improved. The tiles of 100x100 meter are quite large. It would be better to take a more detailed grid or splitting up the tiles. Then still it is difficult to say how many people will be affected by the flood, because it depends on the physical state of a person.

4.5.3 Quantification electricity network disruption

The method used to predict electricity disruption is validated with an expert and found to be useful. However, if a box will actually get flooded depends on location specific characteristics. the boxes which are predicted to flood are checked using google maps. Not all of them are visible but, one box is most probably placed on a bridge. On the map it is placed next to the bridge which makes a lot of difference. If the box is placed on the bridge, it is almost impossible to get flooded. However, to be sure about the location of the box a site visit is needed. It can be concluded that flooding of electricity boxes is highly depend on local characteristics of the area which are not always present in the flood maps. Hence, a site visit to all vulnerable boxes is recommended. Due to this uncertainty, the number of people predicted to be affected by electricity outage is more probably an overestimation then an underestimation.

4.5.4 Hospital disruption

As mentioned, there are some limitations regarding estimations of the accessibility of the road network and electricity network, which have its impact on the analysis of the hospital accessibility as well. Next to that, when studying the service areas it should be taken into account that travel speeds are slower when there is a lot of rain on the road. Also, these service areas are calculated assuming a driver has perfect information about which roads are accessible and which are not. It does not take into account possible chaos which will occur, leading to longer travel distances.

To increase the knowledge on accessibility of the hospitals, it would be good to expand the area and the road network. Because some areas at the edges may seem hard to reach or even disconnected, but are in reality accessible by the roads surrounding the study area. Also, there are more hospitals in the area. To accurately assess the accessibility of hospitals of the inhabitants in case of a flood event, these other hospitals should also be taken into account.

4.5.5 Supermarket disruption

The conclusions about supermarket disruption are based on an unreliable dataset, thus limitations and recommendations are based on the method. The proposed method only looks at the accessibility of the supermarkets. It does not take into account the number of inhabitants in that area, or the size of the supermarkets. By including this information, it could be possible to quantify the number of people who will be affected by the disruption. Also, it does not take into account the possible risk of disruption in the supply process of supermarkets. This will largely depend on the duration of the flood, the size of the supermarkets and the number of inhabitants it serves. Lastly it could be argued that 10 minutes walking time to a supermarket is still not a lot. This depends on the physical conditions of the inhabitants. For example, if a neighbourhood houses many elderly people and the area becomes relatively inaccessible to supermarkets, this is a larger problem then for areas with typical younger inhabitants.

5. Case Part II Resilience of the user

5.1 Introduction

Not much research has yet been conducted on what accepted levels of critical infrastructure disruption are according to the user. There is no established methodology how to research this and what factors to include. As mentioned in the literature section of this research, within the IMPROVER project a start is made on this subject using a questionnaire-based approach. This research extends on that study by taking a different approach and analysis technique.

Specifically one pilot study in Barreiro, Portugal is interesting because it was carried out on a large scale and gives input how to measure tolerance levels (Petersen, Lundin, et al., 2020). This project served as a base for this research. However, a different approach is taken. The main difference in research technique is posing the question as: "*What does the average person think is an acceptable duration of disruption"* versus *"What are the chances a person will not accept a disruption of a certain duration"*. The first version focusses on finding a duration of disruption that is acceptable to the general infrastructure user. However, no trade-off was included in the decision process of the user in question. Decisions about whether or not to accept a situation will in general be based on some sort of trade-off. In this research a trade-off is included in the form of asking someone whether or not a certain disruption would be unacceptable to the level that the respondent would consider to move to another living environment. The outcome is the chance a person will or will not accept a certain disruption. Furthermore this research includes disruption to multiple networks and introduces the variable 'recurrence time of an event'. Hence, this research adds to existing research by proposing a new method to research acceptance levels of critical infrastructure disruption, including different networks and the variable *recurrence time.* The previous research included some socio-demographic characteristics, which can be used for comparison. In this research also some new characteristics are added.

5.2 Method

A questionnaire with different disruptive scenarios was designed to measure the users' tolerance levels of critical infrastructure disruption. The results of the questionnaire are used to run an ordinal regression analysis. In this case, the users of the critical infrastructures are the inhabitants of the inner city of The Hague. They were contacted through the city panel of the municipality. The panellists expressed their likelihood of moving to a different environment when presented with different disruptive scenarios. The ordinal regression analysis resulted in parameters describing the likelihood users do not tolerate the disruption of different infrastructures, given certain demographic features, duration of the disruption and the recurrence time of the disruption.

5.2.1 Ordinal logistic regression

A common methodology to analyse data with one dependent variable and multiple independent variables is multiple regression. However, in standard multiple linear regression the dependent variable is continuous. In ordinal logistic regression it is categorical.

A categorical dependent variable means that each observation falls in one of the possible categories. The categories can be ordered in terms of more or less. The aim of the method is to predict the chance that a specific observation will fall into a certain category given the dependent variables. Just like standard regression, ordinal regression determines which independent variables have statistical influence on the dependent variable, and how large this influence is. Lastly it gives information on how well the model is able to predict the depend variable.

For independent categorical variables can be estimated what the chance is that a certain observation will fall in a higher category of the dependent variable. This is called the odds ratio. For continuous variables it can be estimated what the chance are that with the increase of a single unit of the independent variable, the dependent variable will fall into a higher category.

There are four assumptions which need to be fulfilled: 1) the dependent variable is ordinal; 2) the independent variables are either continuous, categorical or ordinal (however, these will be treated as categorical by the model); 3) there is no multicollinearity, meaning no highly correlated independent variables; 4) the data has proportional odds. This means that each independent variable will have the same effect on the distribution of the categories of the dependent variable. The independent variables only influence the relative increase or decrease of this ratio between the different categories of the dependent variable.

The basic formula of ordinal logistic regression writes:

$$\ln\left(\frac{Prob(cat. \leq j)}{prob(cat. > j)}\right) = c_j + \sum \alpha_k X_k$$

In this formula c_j is a parameter for each (except the last one) category j of the dependent variable. Parameters α are specific to the independent variables X. As shown, the dependent variable is estimated as a cumulative logit. It is the natural log of the probability that the dependent variable will fall in a certain category, divided by the probability it falls in the higher categories. The dependent variable is a cumulative logit, because it says something about the ratio between all categories. Hence The assumption of proportional odds needs to hold, because the parameters α do not influence the odds ratios between the categories of the dependent variable (Laerd Statistics, 2013).

5.2.2 City panel

The municipality of The Hague offered the opportunity to make use of their city panel, and thereby being able to survey the exact group of interest: the inhabitants of The Hague which live in the same area for which the flooding consequences were studied. In total the city panel consists of 5100 members living in all different neighbourhoods of The Hague. They are used to filling out questionnaires about twice a month. It is a rather representative group of the inhabitants, with only an under-representation in lower educated class and age group 16-29 years. Next to the residential location of the panellists, basic socio-demographic information is available of each of the panellist. Each panellist confirms with the privacy statement of the executive party Steda, as stated on their website (Steda, n.d.).

The panellists in this neighbourhoods of the study area, as presented in figure 18 in the methodology chapter, received an e-mail with a short description of the research and the request to fill in the survey either on their smart phone or computer through a link. The survey was set out in January 2021 to 1677 panellists and filled in by 794 respondents, which is a response rate of 47.35%.

The downside of using the city panel was that there were some limitations regarding the form of questionnaire. The survey could not take longer than 12 minutes and should be easy to understand for all groups of people. Another limitation regarded the software in which the survey was programmed. It allowed to randomise the questions posed to panellist, but not to include a set of more questions of which a panellist would get randomly assigned a few. For the design of the experiment this was a downside, which will be elaborated on in the subchapter *research design*.

5.2.3 Survey set-up

The panellists were asked to imagine the scenario of a heavy rain event of a few hours which would temporarily flood parts of the city. In order to prepare the respondents, some introductory questions were posed such as 'do you worry about the consequences of a flood?' and 'do you have an emergency stock at home?'.

The main part of the survey consisted of presenting the panellists with 9 different scenarios regarding the disruption of infrastructures. The five infrastructures which were also present in the research of chapter 4 were included in the scenarios: the electricity network, the mobile network, accessibility of the streets, emergency aid of the hospital and access to supermarkets. Each scenario consisted of three out of the five types of infrastructures with a varying length of the disruption. The panellists asked to what extent they agreed to the following statement using a five point Likert scale: "*If the following scenario would occur once every two years, I would look for a different living environment*". Answers could vary between *Strongly agree, Agree, Neither agree nor disagree, Disagree, Strongly disagree.* This type of posing questions is common when researching acceptance levels and using a Likert scale (an example is presented by Heins & Heijmans, (2020)).

If the responded replied with one of the first three options, the same question and scenario would be posed, only now with the recurrence time of the event being 10 years. If the respondent replied *Disagree* or *Strongly disagree*, the next question with a new scenario would pop up. An example of one of the questionnaires can be found in Appendix H. Appendix H shows a translation of part of the survey. It must be noted that the survey was written in Dutch and a lot of effort was spent on using the exact phrasing to give as much information in as little words. Nuances might have been lost in translating this to English.

The five infrastructure variables all have three levels as described in table 9. The levels regard the hours of disruption in the network. These were composed in consultation with two experts on urban hydrology and critical infrastructures and by studying the consequences of a peak rain event in Copenhagen in 2012 (Danish Emergency Management Agency, 2012). The levels of disruption are rather extreme given the fact that a recurrence time of two and ten years is posed. This might seem unrealistic. However, in order to gain insights in what disruption people tolerate the scenarios should be rather extreme. Because if the scenarios are not disruptive enough, most respondents will fill in to accept the disruption. This could lead to too few variation in the data to be able to run a regression with significant outcome. Next to that, all levels of variables had to be combinable with each other without being unrealistic. For example, one hour electricity outage with 24 hours of hospital Emergency Room closure is not realistic as a consequence of a flood.

Table 9: Attributes and levels of independent infrastructure variables.

	Level 1	Level 2	Level 3
Electricity	6 hours disruption	12 hours disruption	48 hours disruption
Mobile network	6 hours disruption	12 hours disruption	48 hours disruption
Street network	6 hours disruption	12 hours disruption	24 hours disruption
Shops	1 day- only some supermarket are open	1 day all supermarkets are closed	2 days all supermarkets are closed
Hospital ER	3 hours disruption	12 hours disruption	24 hours disruption

In the questionnaire there was not a lot of space for elaborating on the consequences of the disruption on the networks. The explanations were as follows:

Electricity: network is down for X hours.
Mobile network: you are unable to call or use internet on your phone for X hours.
Streets: streets are flooded, hence you are unable to drive your car or use public transport for X hours
Accessibility shops: one day all shops are closed, except for some supermarkets / X days all shops are closed
Hospital ER: all emergency rooms are closed for X hours.

5.2.4 Research design

The number of different scenarios to be tested on the users had to be minimalised because one participant was only allowed nine questions. Also, because the scenarios could not be too complex to evaluate, only three variables could be tested per scenario. The solution to these limitations was to present the participants with only one scenario per question and ask them to score it on a Likert scale. To increase the number of different scenarios to be scored, three different questionnaires were composed and randomly distributed amongst the participants. These three questionnaires concerned different compositions of 3 out of 5 the infrastructure variables, see table 10. There is some overlap between the questionnaires to be able to compare the effects of the infrastructure variables with each other Within these questionnaires the questions were posed in a random order.

Table 10: Infrastructure variables present in each scenario set.

Scenario set 1	**Scenario set 2**	**Scenario set 3**
Electricity	Electricity	Electricity
Mobile network	Mobile network	Street network
Shops	Hospital	Hospital

Each scenario set combined three infrastructures at three different levels which in a fractional factorial design needs a minimum of nine tests. The combinations of these variables and levels were made as prescribed by Hahn and Shapiro (1966) using experimental code plan 16a.

Having three scenario sets of nine tests, leads to 27 tests in total. These 27 scenarios were randomly distributed across three questionnaire versions, making sure every version had three questions of each scenario set in it. Thus, each panellist was presented nine scenarios, three from each scenario set.

In the dataset all answers to each presented scenario with both recurrence times are presented as one observation, leading to 14292 observations (794 respondents x 9 scenarios x 2 recurrence times).

5.2.5 Variables

The dependent variable of this research is the answer to the question how likely it is that the respondent will look for another living environment when confronted with the scenario, on a five-point Likert scale. For analysis, the answers *strongly agree* and *agree* were combined as well as the answers *strongly disagree* and *disagree.* This led to a three-point Likert scale which increases the predictive power of the ordinal regression model. The category *strongly agree + agree* had 2,678 observations, the category *neither agree nor disagree* 2,707 observations. The most popular answer was the category *strongly disagree + disagree* with 8,907 observations.

The independent variables can be divided in infrastructure variables and socio-demographic variables. The infrastructure variables are composed according to the levels in table 9 and distributed according to table 10. Hence, the variable *electricity* was present in all scenarios (14292 observations), *mobile network* and *hospital* were present in two out of three scenarios (9528 observations), and *street network* and *shops* in one out of three scenarios (4763 observations).

The variables have been included in the model in two different ways, leading to two different models. In the first method, the levels of the independent variables are effect coded according to the scheme presented in Table 11. In this way the reference category of the disruption is the average of the disruption. Another advantage is that if the variable is not present in the scenario, it can be coded as 0-0, which then does not influence the estimated parameters.

Table 11: Effect coding scheme of infrastructure variables.

	Level 1	Level 2	Level 3
Variable X1	1	0	-1
Variable X2	0	1	-1

The second method was to transform the levels of disruption into a continuous scale of hours of disruption. This was not possible for the variable *shops* because it includes a variation between 'fully closed' and 'some supermarkets are open'. The advantage of this method is that it allows for easy comparison of the four infrastructure variables with each other. Moreover, it gives a parameter which can be read as the marginal change in valuation per hour. A downside is that it assumes that if a variable was not present in the scenario, it was still assessed as zero hours disruption, which can be argued if this is a valid assumption.

The model includes eight socio-demographic characteristics, which are listed in table 12. The categories which are highlighted are the largest, and are therefore chosen to be the reference category.
The first five variables originate from the city panel data on the panellists. Some variables are altered, for example merging categories because the groups were too small. The panel data also included information on background and residency on neighbourhood level. These variables were left out.

The last three variables were obtained from the survey as introductory questions.

Table 12: Frequency table of socio-demographic variables.

Variable	Categories	Frequency	percentage
Gender	Woman	6642	47.7%
	Man	7290	52.3%
Household	Other	792	5.7%
	Single person household	5022	36.0%
	Family	2826	20.3%
	Two-person household	5292	38.0%
Education	Lower	684	4.9%
	Middle	2322	16.7%
	High	10926	78.4%
Age categories	16-26 years	684	4.9%
	30-39 years	1638	11.8%
	40-49 years	2880	20.7%
	50-59 years	3096	22.2%
	60-69 years	3330	23.9%
	70+	2304	16.5%
District	Segbroek	5094	36.6%
	Scheveningen	1800	12.9%
	Centrum	7038	50.5%
House owner or tenant	Tenant	3636	26.1%
	Owner	10296	73.9%
Expected stay in current house	1 year	936	6.7%
	2-4 years	1836	13.2%
	5-10 years	2592	18.6%
	11 years or longer	8568	61.5%
If a person worries about flooding	Yes	2196	15.8%
	a little	5130	36.8%
	No	6606	47.4%

The model includes the variable *recurrence time*. This variable has either the value two years or ten years. Due to the setup of the survey, the panellists would first rate the given scenario in case that it would occur once every two years (thus a recurrence time of two years). If the respondent answered either dis*agree* or *strongly disagree*, the respondent would not get the same question with recurrence time of ten years. Because, now it is assumed that for a longer recurrence time the respondent will give the same answer. Hence, this answer would be coded as a missing value, and later recoded as *strongly disagree.*

Lastly, the model includes the variable *Scenario Sets*, which checks if there is a significant difference between the rating of the given combinations. This variable is mainly used to check if the methodology is to be trusted, no effect of this variable is expected.

5.3 Results

The dataset was analysed using an ordinal regression model in SPSS. Different configurations of variables were used to find the best model fit. The variables were extensively checked for interaction effects which were likely to be present. For example one could expect an interaction between age categories and hospital disruption, indicating that elderly people experience the disruption of the emergency rooms worse. Also an interaction between age categories and mobile phone network was expected, showing older people value the mobile phone network less than younger people. However, no significant interaction effects were found which could be explained and increased the model fit. Hence, these were left out of the models. The set-up of the experiment does not allow to check for interaction between the different infrastructure variables.

The results of the ordinal regression are presented in table 13. As mentioned, two different models were used to interpret the infrastructure variables in two distinct ways: a continuous model and one using effect coding.

Table 13: Parameter estimates of independent variables for both models.

	Continuous variable model Nagelkerke ρ^2 0.164		Effect coding model Nagelkerke ρ^2 0.165	
Thresholds dependent variable	Parameter estimate	Significance	Parameter estimate	Significance
Likert answer Strongly agree + agree	-3.242	0.000	-2.850	0.000
Likert answer Neither agree nor disagree	-2.156	0.000	-1.763	0.000
Infrastructure variables				
Electricity continuous	-0.014	0.000		
Electricity X1 (6 hours disruption)			0.232	0.000
Electricity X2 (12 hours disruption)			0.119	0.000
Mobile network continuous	-0.003	0.005		
Mobile network X1 (6 hours disruption)			0.111	0.000
Mobile network X2 (12 hours disruption)			-0.033	0.279
Street continuous	-0.005	0.222		
Street X1 (6 hours disruption)			0.110	0.013
Street X2 (12 hours disruption)			-0.090	0.037
Hospital continuous	-0.007	0.004		
Hospital X1 (3 hours disruption)			0.092	0.003
Hospital X2 (12 hours disruption)			-0.025	0.412

Shops X1 (1 day – only some shops open)	-0.067	0.125	-0.068	0.119
Shops X2 (1 day- all shops closed)	0.024	0.589	0.025	0.565
Recurrence time reference: 10 years	0		0	
2 years	-1.174	0.000	-1.175	0.000
Scenario set reference: set 3	0		0	
Scenario set 1	0.039	0.645	-0.007	0.871
Scenario set 2	-0.022	0.658	-0.094	0.031
Socio-demographic variables				
Gender reference: Male	0		0	
Female	0.164	0.000	0.164	0.000
Household reference: two persons	0		0	
Other	0.210	0.012	0.210	0.012
Single person	0.008	0.848	0.008	0.851
Family	-0.095	0.073	-0.096	0.070
Education reference: high	0		0	
Middle	-0.166	0.001	-0.166	0.001
Low	-0.610	0.000	-0.611	0.000
Age reference: 60-69 years	0		0	
16-29 years	-0.328	0.001	-0.328	0.001
30-39 years	-0.099	0.139	-0.099	0.141
40-49 years	-0.100	0.087	-0.100	0.087
50-59 years	-0.223	0.000	-0.224	0.000
70+	0.234	0.000	0.234	0.000
District reference: Centrum	0.000		0.000	
Segbroek	0.148	0.000	0.149	0.000
Scheveningen	0.044	0.438	0.044	0.440
Reference: house owner	0.000		0.000	
Tenant	0.109	0.023	0.108	0.023
Expected stay reference: 11 years or longer	0		0	
5-10 years	-0.264	0.000	-0.264	0.000
2-4 years	-0.329	0.000	-0.330	0.000
1 year	-0.609	0.000	-0.609	0.000
Worry about flooding: answer ‘No’	0.000		0.000	
Answer ‘A little’	-0.887	0.000	-0.887	0.000
Answer ‘Yes’	-0.942	0.000	-0.943	0.000

Assuming all infrastructure variables are 0 and base levels of other variables, the parameter estimates can be transformed into odds ratio’s that a person would choose the combined answers of A*gree* or *Neither agree nor disagree* using the following formula:

$$Probability\ choosing\ 'Combined\ Agree' = \frac{1}{(1 + e^{-(threshold\ parameter\ Agree - \alpha)})}$$

$$Probability\ choosing\ ('Combined\ Agree' + 'Neither') = \frac{1}{(1 + e^{-\ (threshold\ parameter\ Neither - \alpha})}$$

In this formula, α is the parameter of an independent variable. If the independent variable is the reference category, the parameter is zero. The odds of a person choosing 'Neither' can be calculated by subtracting the odds of choosing 'Combined Agree' from the odds of choosing 'Agree + Neither'.

Using this formula, the probabilities for choosing the three Likert categories can be established for the two models which are presented in table 14.

Table 14: Distribution of the categories of the dependent variable for the two models.

	Continuous model	Effect coding model
Combined answers Agree	3.76%	5.47%
Neither	6.61%	9.17%
Combined answers Disagree	89.62%	85.38%

Thus, assuming a person with socio-demographic characteristics as defined as the reference groups, the model would predict the odds of this person choosing the combined answer Agree as 3.76% for the continuous model, and as 5.46% for the effect coding model. The values are significant at the 0.000 level. The difference can be explained by the fact that in the effect coding model, al infrastructure variables are estimated on average disruption, while in the continuous model the disruption for all variables are zero hours, except for shops which has average disruption. The reference category of recurrence time is ten years.

The combined answers 'Agree' means a person agreed to look for another living environment as a consequence of the presented disruption, and can hence be regarded as the tolerance level for infrastructure disruption.

Table 15: Model fitting parameters.

	Continuous variable model		Effect coding model	
	Chi-Square	Significance	Chi-Square	Significance
Model fitting information				
Intercept vs prediction	2068.743	0.000	2081.221	0.000
Goodness-of-fit				
Pearson	25010.466	0.004	25010.352	0.003
Deviance	21660.967	1.000	21648.489	1.000
ρ-Square				
Nagelkerke		0.164		0.165
Cox and Snell		0.138		0.139
McFadden		0.080		0.081

Table 15 provides the model fitting parameters. For both models it is significant at 0.000 level that the model predicts the results better than an intercept-only model. The Pearson and Deviance test assess the goodness-of-fit of the models, though it is not an ideal measure because there are a lot of empty cells due to the high number of variables. Still the Deviance test scores well for both models (p=1.000), and for the Pearson model scores are significant at the 0.004 and 0.003 level. ρ-Square tests give information on the amount of variation in the data explained by the model. For this model the Nagelkerke value is used, which should give a value of at least 0.10 or 0.15 for a decent fit. For these models it is 0.164 and 0.165, which is acceptable.

5.3.1 Infra variables – effect coding model

First the infrastructure variables are explored using the effect coding model, which enables to look at the differences between the three levels. Because both parameters for shop disruptions are found to be insignificant, these are left out of the analysis. Figure 46 explores the relative influence of the attributes at all measured levels, by taking the exponent of the parameters. The lower the value, the more likely someone will not accept the given disruption. The further the deviation from 1, the more influence a variable has. Attribute levels with an asterisk have parameter values which are not fully significant or the results cannot fully be explained. Light blue attributes and levels got at least one insignificant parameter (p>0.05). The variable *street* has significant parameters, but an outcome which does not appear realistic.

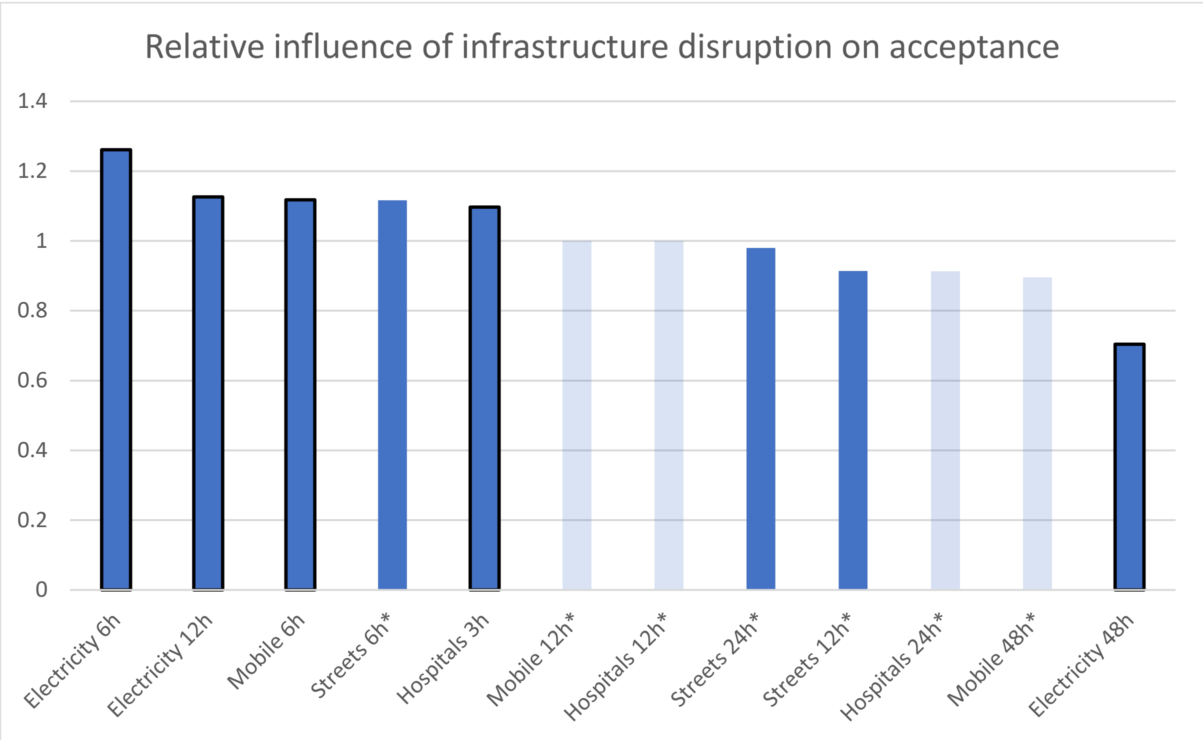

Figure 46: Relative influence of infrastructure disruption of different attributes and levels on acceptance.

This first assessment shows at both ends that *electricity* disruption of 6 hours is most accepted, compared to the other attributes and levels, and *electricity* disruption of 48 hours the least. The disruption of the electricity network thus has a strong influence in general. The influence of disruption tolerance of 12 hours electricity, 6 hours mobile network and 3 hours no hospitals is comparable. Parameters of the attribute *street* show more tolerance towards 24 hours disruption, then for 12 hours disruption, though the two parameters for street network disruption are significant (p=0.013 and p=0.037).

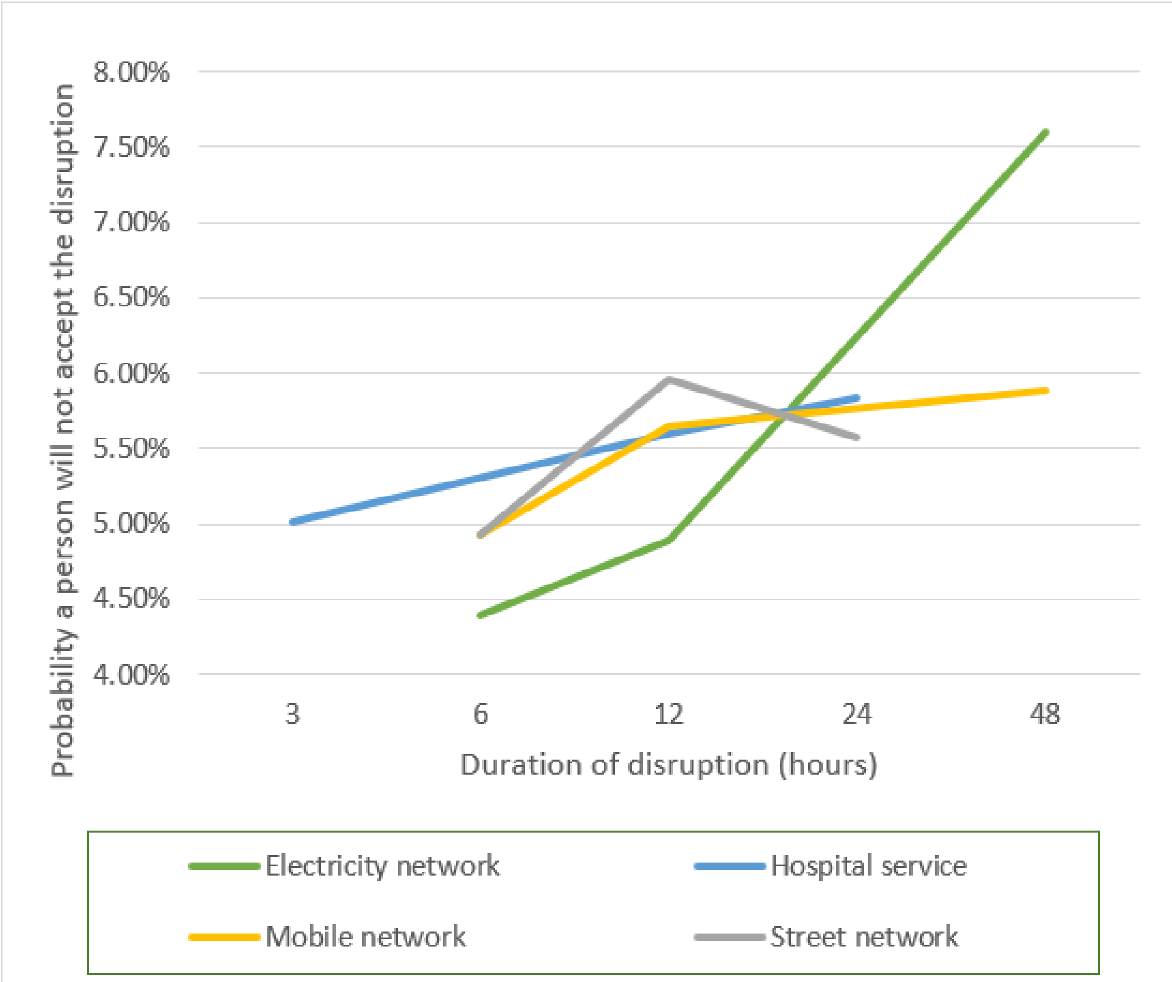

Figure 47: Results of the infrastructure variables of the effect coding model in the category not accepting the disruption (recurrence time 10 years).

Figure 47 gives the probability of panellists answering with the combined answer 'Agree' for each level, and connects these points with a trendline. The exact probabilities are presented in Table 16. The values should be interpreted as the percentage chance that a panellist, in the reference categories, will not accept the infrastructure disruption at the given levels. For all infrastructures except for *streets* there is a clear upward trend visible. The upward trend was expected, since more disruption is supposed to lead to less tolerance. The conflicting results of *streets* need further investigation.

Electricity shows a clear jump between level 2 and 3, which is not observed for the other infrastructures and it has the steepest trend line in general. Disruption of the hospital of 3 hours is comparable to the disruption of the mobile network for 6 hours. From durations over 6 hours the two follow the same trend line.

Table 16: Probabilities that a person would not accept different disruptions in the effect coding model.

	Duration of disruption (hours)				
	3	6	12	24	48
Electricity network		4.39%	4.89%		7.59%
Mobile network		4.92%	5.65%		5.89%
Street network		4.93%	5.96%	5.57%	
Hospital service	5.01%		5.60%	5.83%	

5.3.2 Infrastructure variables – continuous model

When using the continuous model the marginal difference per hour disruption of the infrastructure variables can be obtained. This is done using the following formula:

$$Probability\ 'Agree' = \frac{1}{1 + \mathrm{e}^{-(-3.242\ -\mathrm{h}*\beta-\ \delta)}}$$

Here h being the disruption in hours, and β being the parameter estimate of the infrastructure variable. The recurrence time parameter here is δ, being -1.174 in case of an event happening once in 2 years, and zero once in 10 years.

The parameters for infrastructures *Electricity (*-0.014, p=0.000)*, Hospital* (-0.007, p=0.004 and *Mobile network* (-0.003, p=0.005) are significant. Using formula (X) the tolerance levels can be obtained and are visualised in figure 48 and 49. The predicted values can be found in Appendix I. The parameter of *street* network disruption is left out, because of the insignificant parameter (p=0.222), but has a comparable parameter to *hospital* and *mobile network* (-0.005).

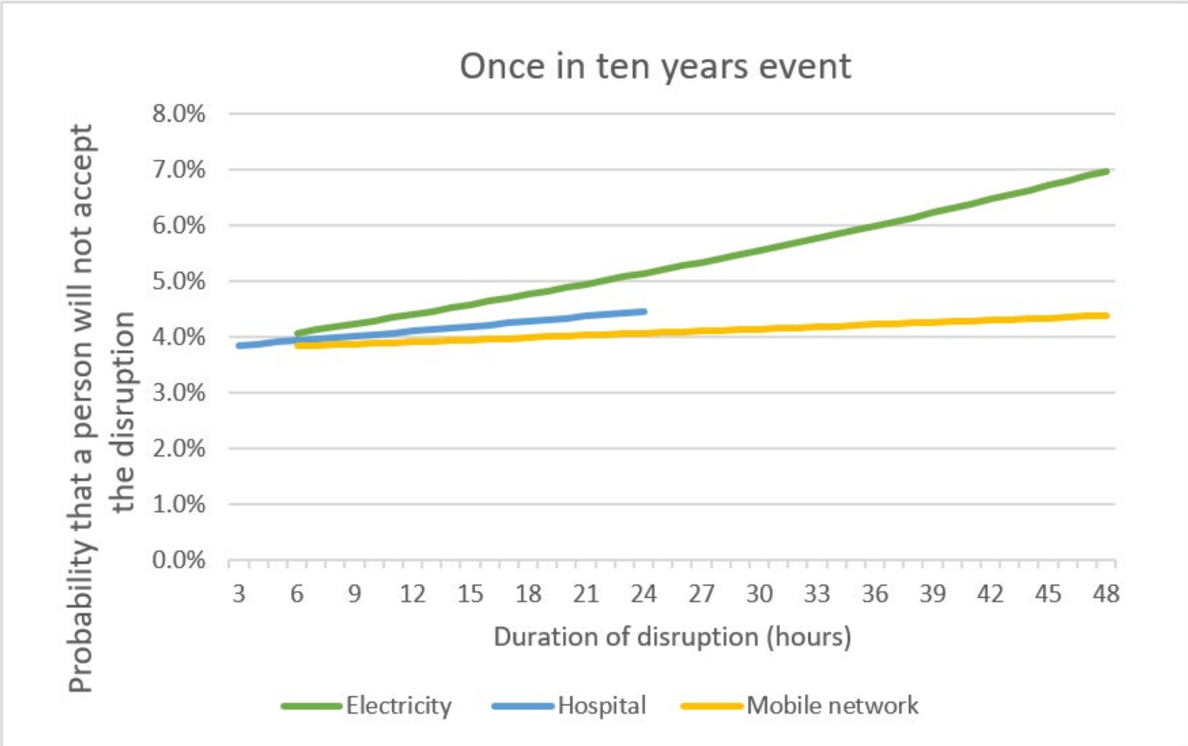

Figure 48: Results of the significant infrastructure variables of the continuous model in the category not accepting the disruption (recurrence time 10 years).

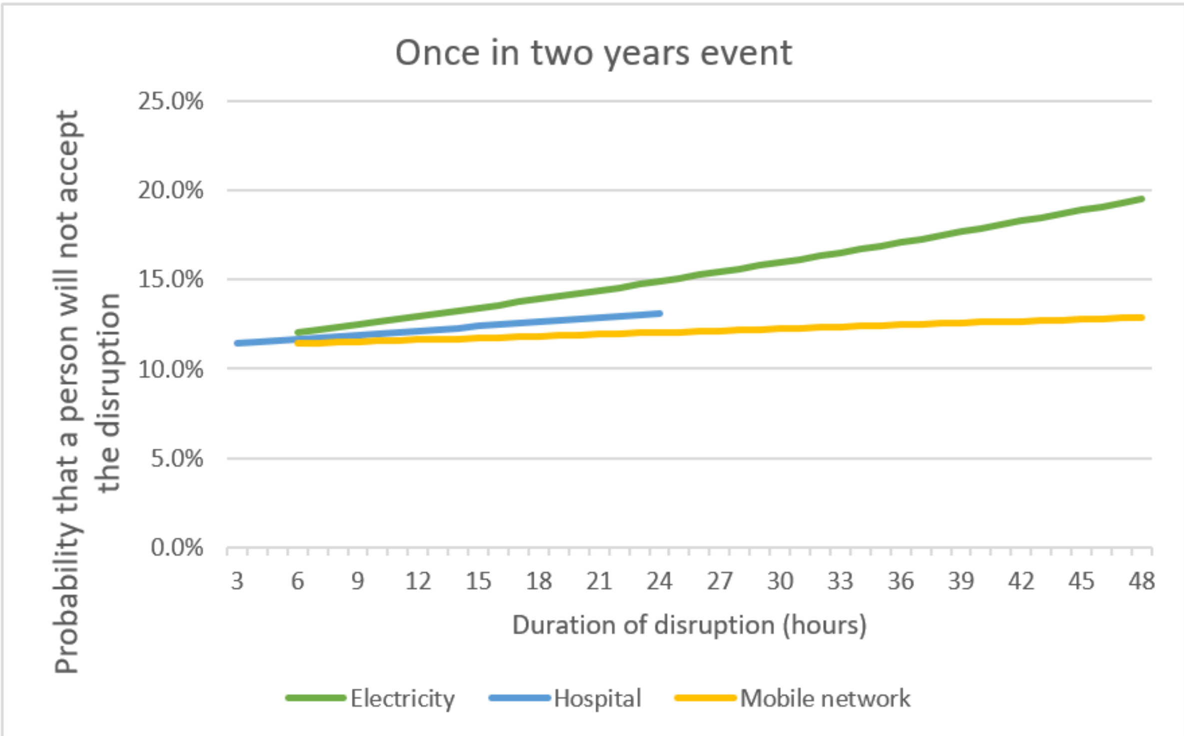

Figure 49: Results of the significant infrastructure variables of the continuous model in the category not accepting the disruption (recurrence time 2 years).

From these two graphs it is clear that *Electricity* has the highest influence on people's tolerance levels, followed by *Hospital* and then *Mobile network*. In this model there is a larger difference between tolerability of the latter two infrastructures than in the effect coding model.

5.3.3 Socio-demographic variables

When looking at the influence of socio-demographic variables on tolerance levels regarding critical infrastructure disruption, the model with continuous infrastructure disruption is used. When taking the exponent of the parameter, the odds ratio is obtained. This odds ratio gives the chance that a person with certain socio-demographic characteristic will score higher or lower on the dependent variable (higher/lower acceptance of tolerance), then a person with social-demographic characteristics from the reference category. An overview of these ratios is presented in table 17.

Table 17: Parameter estimates and odds ratios of the socio-demographic variables.

Socio-demographic variables	Parameter estimate	Odds Ratio	sig.
Gender reference: Male	0.000		
Female	**0.164**	**1.180**	**0.000**
Household reference: two persons	0.000		
Other	**0.210**	**1.230**	**0.012**
Single person	0.008	1.010	0.848
Family	-0.095	0.910	0.073
Education reference: high	0.000		
Middle	**-0.166**	**0.850**	**0.001**
Low	**-0.610**	**0.540**	**0.000**
Age reference: 60-69 years	0.000		
16-29 years	**-0.328**	**0.720**	**0.001**
30-39 years	-0.099	0.910	0.139
40-49 years	-0.100	0.900	0.087
50-59 years	**-0.223**	**0.800**	**0.000**
70+	**0.234**	**1.260**	**0.000**
District reference: Centrum	0.000		
Segbroek	**0.148**	**1.160**	**0.000**
Scheveningen	0.044	1.040	0.438
Reference: house owner	0.000		
Tenant	**0.109**	**1.120**	**0.023**
Expected stay reference: 11 years or longer	0.000		
5-10 years	**-0.264**	**0.770**	**0.000**
2-4 years	**-0.329**	**0.720**	**0.000**
1 year	**-0.609**	**0.540**	**0.000**
Worry about flooding: no	0.000		
A little	**-0.887**	**0.410**	**0.000**
Yes	**-0.942**	**0.390**	**0.000**

Cells have bold fond if their parameters are insignificant (p<0.05), and blue if their influence is high (below 0.60 or above 1.40).

There is a small but significant (p=0.000) difference visible between man and women, the odds ratio is exp(0.164)=1.18, meaning that the chance that a women accepts infrastructure disruption is 1.18 times higher than men.

When looking at differences between education levels, there seems to be downwards trend: the lower the education level, the less tolerance to infrastructure disruption. Differences between higher and lower education levels are large: the amount of lower educated people not tolerating disruption almost doubles compared to high educated people (odds ratio of 0.540, p=0.000). People with high education levels are 1.176 times more likely to accept disruption compared to middle education levels (odds ratio of middle education 0.850 p = 0.001).

Household composition does have influence on the tolerance levels, though differences are small. There does not seem to be a significant difference between a one or two person household. Family households tend to have a slightly lower tolerance for infrastructure disruption compared to two persons households, though this difference is only significant at the 10% level (odds ratio 0.910, p=0.073). There is a significant difference between the group 'other', who are more tolerant to disruption then two persons households (odds ratio 1.230, p=0.012), which includes single parents but possibly also student homes for example.

Between different age groups there can also be differences observed. In general it seems that the older a person gets, the more tolerant to disruption the person is. This effect is significant for the youngest age group being less tolerant (16-29 years p=0.001, odds ratio 0.72), and for the highest age group being more tolerant (70+ p=0.000 odds ratio 1.26). However, the 50-59 years group is rather intolerant (p=0.000 odds ratio 0.80) compared to the reference group being 60-69 years. Between the age of 30 and 49 there does not seem to be a significant difference with the disruption tolerance of the reference group 60-69.

A small difference can be observed in tolerance levels between residents from the Centrum (reference) and Segbroek, the latter having a higher tolerance for disruption (p=0.000, odds ratio=1.16). Comparing residents from Centrum with Scheveningen does not give significant differences. Home owners turn out to have lower tolerances for infrastructure disruption than tenants, though the difference is small (p=0.023 odds ratio=1.12)

A large influence can be found in the variables which describe how long a person plans to stay in the same house regardless of any disruption. In general the shorter someone plans to stay in their current house, the lower their tolerance to infrastructure disruption is. A person expecting to move within one year is twice as likely to not accept the disruption, compared to someone who plans to stay at least eleven years (odds ratio 0.540, p=0.000). All categories are significant at 0.000 level. Comparing a person with plans to move somewhere else in one year results in a reduction in tolerance of almost half. Despite the fact that these parameters have a high influence they can be easily clarified by the way the questions were posed. Because if someone plans on moving anyway, they are more likely to agree to the posed question. Also the variable explaining if someone worries about flooding increases the chance that one will look for a different living environment. Both categories 'to worry' and 'to worry a little' decreases the chance to tolerate disruption by about 2.5 times (odds ratio 'to worry' 0.390, odds ratio 'to worry a little' 0.410 compared to 'not to worry', p=0.000).

5.3.4 Robustness check

The continuous model was run again with two alterations in the dataset to check for robustness. An overview of the models and model fitting information can be found in Appendix J.

The first alteration was to leave out the surveys of panellists who replied the same answer to all the questions. This could indicate that a panellist was not paying enough attention to fill in the survey. On the other hand, if a panellist has a high tolerance for infrastructure disruption, this can mean that the survey will be filled in with all the same answers *strongly disagree*. Hence, this dataset is not used to predict differences, but merely to check robustness. In general the influence of the infrastructure variables increased, but the order remained the same (*electricity* having the highest influence, *mobile network* the lowest). The parameters for the socio-demographic variables did not change much. Only the difference between education categories *lower* and *middle* became smaller.

The second variation in dataset was to only look at the answers of the first question with a recurrence time of two years. This was done because this recurrence time of two years was always asked to all respondents, whereas for 10 years this was sometimes filled in automatically (see the methodology section 'Survey Set-up'). It was not expected that this dataset would give different results since no interaction effect was found between the variable *recurrence time* and the infrastructure variables in the full dataset. Still, it is good to see that the parameters changed as expected: infrastructure variables increased in influence and remained significant. Some socio-demographic variables turned out insignificant, for example differences between middle and high education, and between house owners and tenants. The differences between age categories turned out to be significant for all categories in this model, and a stronger influence of the age category 16-29 having even lower tolerance levels.

5.4 Conclusion

This research offers a methodology to measure and quantify user tolerance levels regarding critical infrastructure disruption. Two different models offer insights in the differences in valuation of these infrastructures. Both models indicate that disruption of the electricity network seems most critical to most people, followed by the availability of emergency rooms in hospitals and lastly the mobile network. Disruption of supermarkets seemed hard to measure, and also the inaccessibility of the street network gave unexpected results.

In case of a disruption once every 10 years leading to six hours electricity loss, between 4.4% (effect coding model) and 4.1% (continuous model) would not tolerate this and move to a different living environment. A three hour closure of emergency rooms in hospitals would result in between 5.0% (effect coding model) and 3.8% (continuous model) of people not tolerating this. Regarding mobile network disruption of six hours, between 4.9% (effect coding model) and 3.8% (continuous model) would not tolerate this disruption. These percentages are relatively low. However, financial and demographic consequences can be high if indeed that percentage of people would move to a safer region.

When looking at socio-demographic characteristics the difference between education class is most notable. According to the continuous model, having a high education in general doubles the amount of tolerance a person has for the given disruptions. This is in line with previous research stating that lower education levels are related to lower tolerances to disruption (Petersen, Lundin, et al., 2020) and that people from lower education classes tend to have higher expectations from infrastructure providers during crisis (Caplan, 2006).

A small but significant difference in age groups can be observed. Younger people (category 26-29 years) tolerate disruption less compared to the reference category. This is in line with previous research stating that younger people are in general are less tolerant to infrastructure disruption (Petersen, Fallou, Reilly, et al., 2018; Petersen, Lundin, et al., 2020). This could on the one hand be explained by the fact that younger people grew up with more electronic devices and hence be more dependent on the electricity and mobile network. It does not explain reliance on hospitals. The difference could also be explained by the assumption that younger people are more flexible regarding their living environment. If they do not tolerate infrastructure disruption, it might be an easier decision to move somewhere else, compared to someone who is older. Previous research states that elderly people are also less tolerant to infrastructure disruption (Petersen, Lundin, et al., 2020), which is contradictory to these results. Again this might be a result of the way the acceptance level is measured.

Differences between districts and even neighbourhoods seem significant, but need further exploration to be able to explain. There are also small but significant differences found between categories of the variables gender, household composition and house owner or tenant.

The continuous model was run again with two alterations in the dataset to check for robustness. One dataset contained only observations with significant variation in the dependent variable. The second dataset contained only observations from the scenarios with a recurrence time of two years. Both results did not differ much from the used model. Hence, the robustness of the outcomes is validated.

5.5 Discussion

A first point of discussion could be if posing the question *if someone would look for a different living environment* as a result of critical infrastructure disruption can be linked to their tolerance levels regarding this disruption. Of course, there will always be other factors which play a role in this decision which unconsciously steer the respondents' answers. The model includes some of these variables, for example the planned duration of stay, but there will be more unobserved characteristics which are not present in the model.

A second point of discussion is the reliability of the chosen scenarios in combination with the recurrence times. It is possible that people found it difficult to imagine these scenarios since they are quite abstract. The survey contained an open question if the respondents would like to leave a message. About one out of ten respondents left a negative message, for example mentioning they found it too difficult to fill in. It is recommended to adjust the scenarios to make it easier for people to relate to. Also, using scenarios of disruptions which people have actually experienced before helps to get reliable results and will make it easier for people to fill in.

Regarding the research design the main improvement would be to make sure all infrastructure attributes and levels are equally represented in the scenarios. Also, a larger experimental design is recommended, to allow to measure interaction effects between the different infrastructure variables. For example, in case of an electricity disruption, it is interesting to measure if one in that case would prefer mobile internet or accessibility to the emergency rooms of the hospital. Also, the fact that no interaction effects were measured between infrastructure variables and socio-demographic variables, even though some were to be expected, needs further investigation.

The continuous model gives insight in how people valuate in increasing amount of disruption per hour. This assumes a linear-in-the-parameters relationship of tolerance and disruption over time. Even though the parameters turned out significant, the results of the effect coding model shows a different trend. It could be argued that within the first six hours of disruption, the tolerance rates decrease more rapidly than in the six hours after that. It is hence advised to include more variation in duration of the disruption and also include shorter durations in future research.

More variation in recurrence times would be interesting to measure because this variable was now only measured at two levels (2 and 10 years), while recurrence times of heavy rains (50 mm in one hour) in the Netherlands start at once every 50 years. In the next part of the research estimations are made for effects of other recurrence times using a linear model. However more research could give insight in the relationship between recurrence time and valuation of disruption.

6. Case Part III Including the users' acceptance levels in the resilience assessment

6.1 Introduction

After presenting methods how to quantify the current level of resilience of critical infrastructure networks, and to quantify the acceptance of disruption of the networks, this chapter aims to demonstrate how to combine the results and applies it to the study area. As Peterson et al. (2019) argue that public tolerance levels are a good indicator for resilience evaluation and demonstrate a first method how a resilience analysis and users analysis can be combined, this research elaborates on that.

The combination of metrics gives an indication which type of disruption present in the study area is perceived worse, and quantifies this in 'number of people not accepting the disruption'. It includes the duration of disruption as well as increasing perceived discomfort of people experiencing disruption over time. The outcome enables decision makers to make deliberate choices what to focus on when improving the resilience of critical infrastructure networks, taking the view of the user and current risks of disruption into account.

6.2 Method

In order to combine the established level of resilience in the study area and the accepted levels of resilience, the metrics and dimensions have to be comparable. An overview of these metrics and dimensions was presented in the methodology section in table 2.

Since the severity of an event and its recurrence time are directly related (presented in table 4 in the methodology chapter), all dimensions fit and the metric for combining the two becomes 'number of people not accepting the disruption'.

Two networks are chosen to demonstrate the methodology: the electricity and road network. These networks allowed for resilience quantification in part I and significant parameters to measure the effects of disruption to acceptance levels were found in part II. In part II two levels of recurrence times were included: 2 years and 10 years, corresponding with a rainfall of 18.9 mm and 35.7mm. These two events are hence chosen. An estimate is made for the acceptance of the recurrence time of 50 years, with corresponding rainfall of 50 mm. This event is also included. However, no resilience triangles are presented for this rainfall event.

The number of people not accepting the given duration of the disruption is obtained with the following formula:

$$Number\ of\ people\ not\ accepting\ disruption = \max_{t}(amount\ of\ people\ affected_t * not\ acceptance\ rate_t)$$

The number of people not accepting the disruption is calculated for each point in time t that there is a disruption and is visualized. The highest value is the indicator how many people will not accept the disruption of the event.

6.2.1 Input current level of resilience

The resilience triangles of the two networks are established in chapter 4 and presented in figure 35 and 37 are used as input. The number of people affected by the 18.9mm, 35.7 mm and 50mm rainfall are used and presented in table 18 and 19. As mentioned in chapter 4, the predictions on duration of the event and restoration time of the networks are based on expert judgement. Not all values are known at each point in time, these are interpolated assuming a linear function.

Table 18: Number of people without electricity over time in case study area.

	point in time (hours), rainfall ends at t=1						
Type of rainfall	**0**	**1**	**2**	**3**	**4**	**5**	**6**
18.9 mm (RT = 2 years)	0	808	539	269	0	0	0
35.7 mm (RT = 10 years)	0	1733	1733	1155	578	0	0
50 mm (RT=50 years)	0	1733	1733	1733	1155	578	0

Table 19: Number of people affected by road network disruption over time in case study area.

	point in time (hours), rainfall ends at t=1													
Type of rainfall	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
18.9 mm (RT = 2 years)	0	18330	12220	6110	0	0	0	0	0	0	0	0	0	0
35.7 mm (RT = 10 years)	0	41330	38110	34890	31670	28450	25230	22010	14673	7337	0	0	0	0
50 mm (RT = 50 years)	0	53470	50754	48038	45322	42606	39889	37173	34457	31741	29025	19350	9675	0

6.2.2 Input users' acceptance level of resilience

For both networks the chance a person would not accept a disruption of a certain duration is obtained. However, the levels of the questionnaire included only 6 hours, 12 hours and 24 hours of disruption. Because the durations of disruption of the electricity network takes between 1 and 6 hours, an interpolation is made to obtain the acceptance levels per hour, this is shown in figure 50. It can be assumed that if there is zero disruption, the acceptance level is 100%; the not accepted level is 0%. Using the known not-acceptance levels of disruption of durations 6 hours and 12 hours, the values are obtained per hour using linear interpolation. The table with all used values is presented in Appendix K.

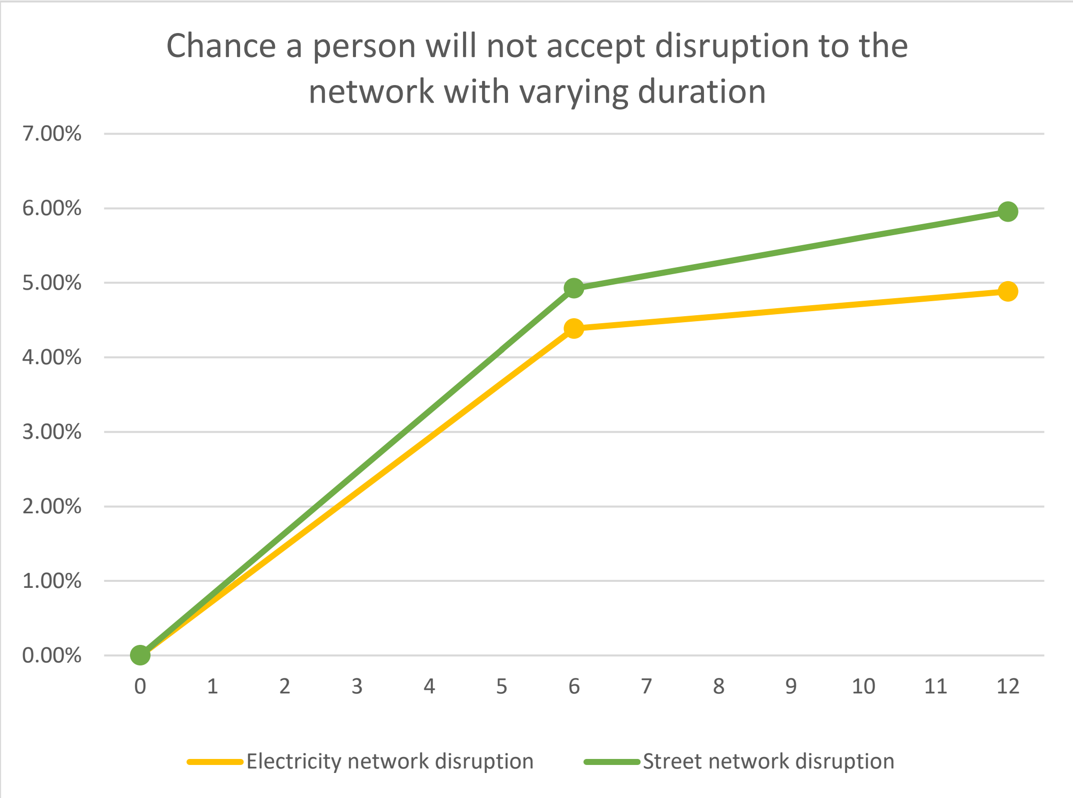

Figure 50: Interpolated values of chances a person will not accept network disruption of certain durations (recurrence time 10 years).

Different scenarios are worked out using the effects of changing recurrence times and different socio-demographic characteristics on acceptance of disruption. Appendix L presents an overview of the parameters which are used in the estimations.

The influence of the recurrence time of an event is also estimated in part II. However, only the parameters for an event with the recurrence time of 2 years and reference category 10 years are known. The effects of other recurrence times (1 year, 5 years, 25 years and 50 years) are estimated using a linear inter/extrapolation. Especially the values for RT=25 and RT=50 years are illustrative to incorporate the effect of climate change which will result in increasing recurrence times of heavy rainfalls. The used increased recurrence times are the 2050 'worst case' scenario of the KNMI, as explained in chapter 4. However, more research to establish the relationship between recurrence times and valuation of disruption is necessary. Figure 51 and table 20 show the estimations of the effects of the different recurrence times.

Table 20: Estimated effects of recurrence times to acceptance of disruption.

Recurrence time (year)	Effect
1	-1.32188
2	-1.175
5	-0.73438
10	0
25	2.203125
50	5.875

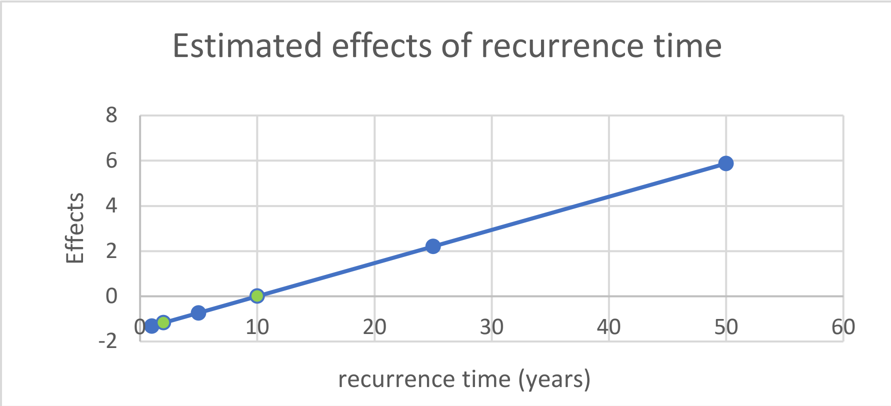

Figure 51: Estimated effects of recurrence times to acceptance of disruption.

6.3 Results

6.3.1 Combined resilience and acceptance triangles

By combining the resilience triangles of the infrastructures per event with the acceptance levels, the distribution of acceptance can be visualized as shown in figure 52 and 53.

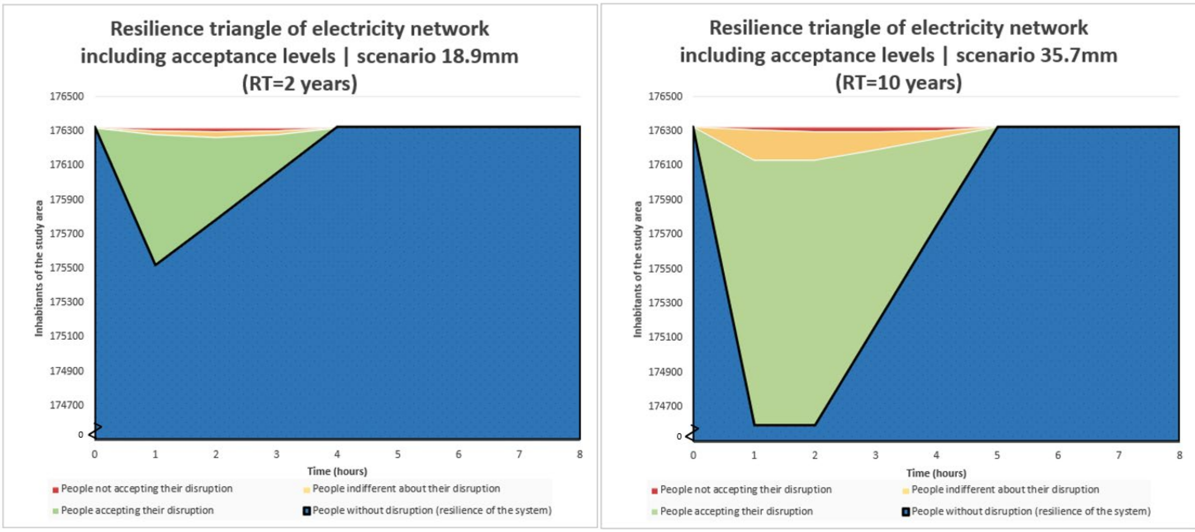

Figure 52: Resilience triangles of electricity network including acceptance levels of two different rainfalls.

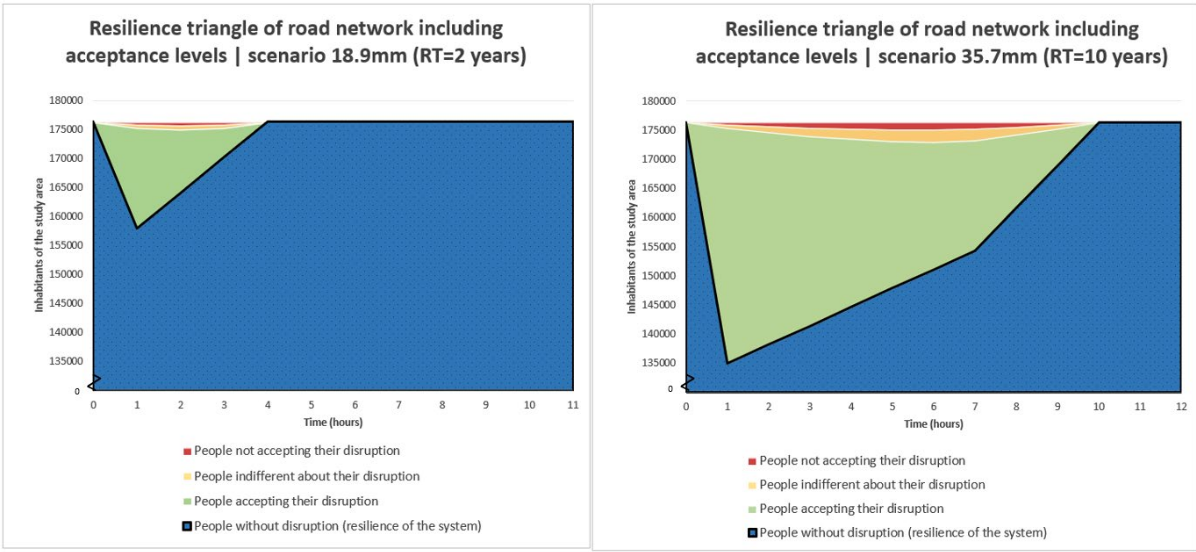

Figure 53: Resilience triangles of the road network including acceptance levels of two different rainfalls.

The blue area gives the number of people who are not affected by the disruption at certain points in time. Chapter four elaborates on the form of these blue areas. The surface of the triangle above the blue area (or for the 35.7mm rainfall event this is more a trapezium), is the area of people who are affected by electricity outage. Within this area there is a certain distribution of people who accept this disruption (in green), who are indifferent (in yellow) and who do not accept this disruption and would consider looking for a different living environment (in red). This distribution is using the socio-demographic characteristics of the reference categories as explained in chapter 5. Figure 53 is showing the disruption to the road network after an 35.7mm rain event already hints that the peak of the disruption (at t=1) is not the peak of the number of people not accepting or being indifferent about the disruption. This peak comes later (t=6). Apparently at that point the rate of not accepting the disruption times the actual disruption is maximized. The next section zooms in on the red areas of the graphs to better study the peaks and forms. Mind that the scale on the y-axis is different between the graphs of the different networks. Chapter 4 revealed that much more people are affected by road network disruption than by electricity outage. Also, the y-axis jumps at the bottom values. These graphs are thus mainly for visualization of the disruption of the event and acceptance at the same time.

6.3.2 No acceptance for disruption – Climate change scenarios

This section zooms in on the red areas from figures 52 and 53. The areas represent how many people at certain points in time do not accept the given disruption and as a consequence would look for a different living environment. Chapter 5 demonstrates that the recurrence time has an influence on the acceptance level of event. Due to climate change the same type of rainfall will increase in recurrence time. This thus influences the acceptance level of the type of rainfall. This is visualized in figure 54 for the electricity network, and in figure 55 for the road network. Appendix M presents all values of the graphs presented in this chapter. Table 20 gives the maximum values.

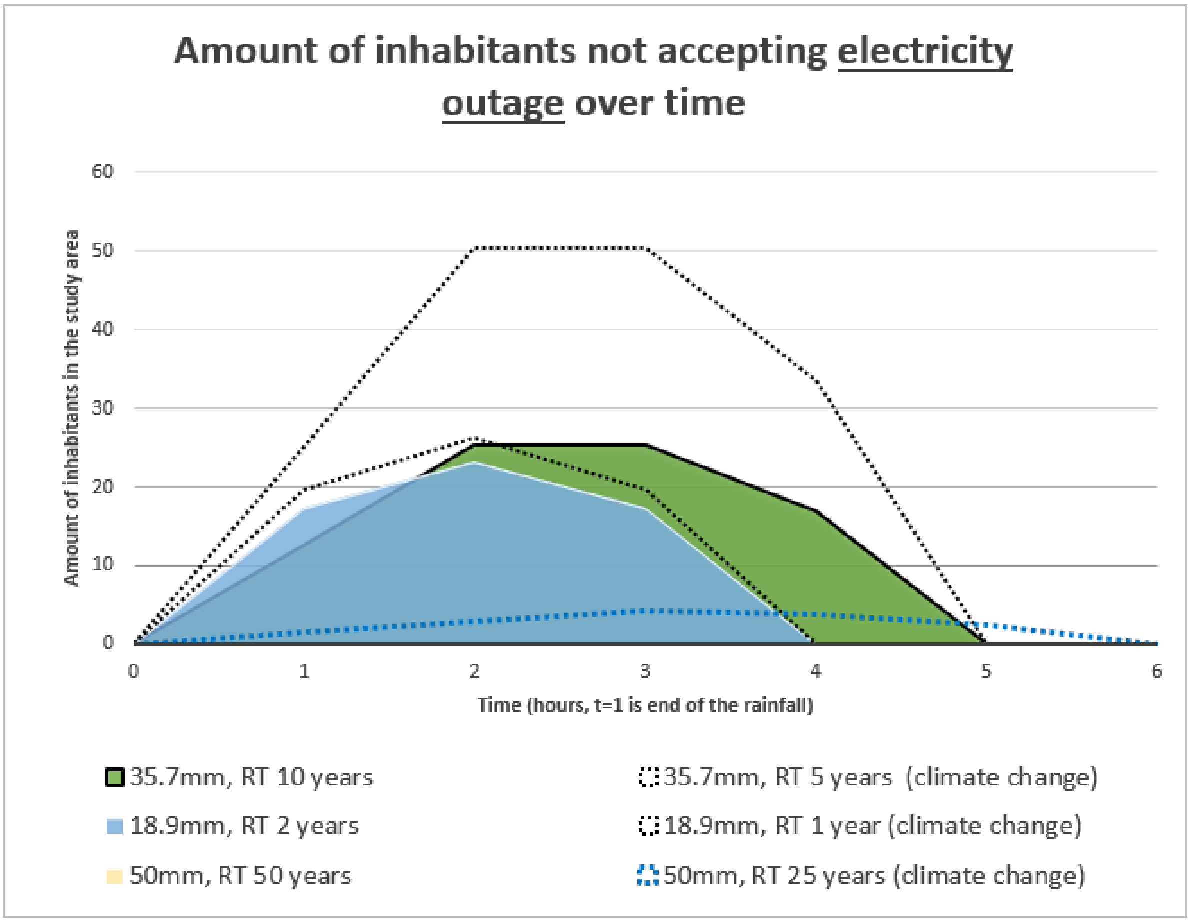

Figure 54: Number of inhabitants not accepting electricity disruption over time including climate change scenarios.

The blue and green areas of figure 52 are the same as the red areas from figure 54, zoomed in and upside down. The 35.7mm rainfall (in green) has a slightly larger area and higher peak than the 18.9mm rainfall (in blue). This may seem evident since the 35.8 rainfall is a more severe event, but it is not perceived as such. Rainfall 18.9 is predicted to happen once every 2 years, which is perceived roughly 3 times worse than an event happening once every 10 years (see chapter 5). At t=1 the number of people affected by electricity outage is twice as much for rainfall 35.7 than for 18.9. Hence, at t=1 the number of people not accepting the disruption is higher for rainfall 18.9 then for 35.7mm. At t=2 the number of people not accepting the disruption for rainfall 35.7 is more than for the 18.9 mm rainfall. This is due to the fact that for rainfall 18.9 the disruption starts deceasing at t=1, while for rainfall 35.7 the disruption is constant until t=3. The number of people not accepting the disruption peaks at t=2 for rainfall 18.9. For rainfall 35.7 the peak lies both at t=2 and t=3. The increase in not acceptance rate compensates with the decrease in disruption.

To compare the two events it is advised to look at the maximum height of the curve. This gives the maximum number of people who would consider moving to a different place as a result of the rainfall. Table 20 gives the maximum values. For the 18.9mm event it is 23 people and for the 35.7mm event the maximum value is 25 people, which is not a big difference.

The dotted lines give the impact of increasing recurrence times of the rainfall events due to climate change scenarios as presented in chapter 4. Each rainfall event has their own shape, but the height of the curve is influenced by the changing recurrence time, which leads to a different not-acceptance rate. The 50mm rainfall with the current recurrence time (once every 50 years) does not have an area nor peak because the not acceptance rate is very low (between 0.00 and 0.01% between t=1 and t=6). If this rainfall would happen once every 25 years the not acceptance rate increases (between 0.08 and 0.50% between t=1 and t=6), which does lead to people not accepting this scenario. The peak is estimated at t=3 and t=4 with a maximum value of 4 people. Compared to the number of people not accepting rainfall 18.9 and 35.7 in the current climate this is low.

The difference of the impact in a changing climate for rainfall 18.9 is relatively low. The maximum shifts from 23 to 26 people (not acceptance rates between t=1 and t=6 shift from 2.16%-12.93% to 2.45%-14.68%). For the 35.7 rainfall there is a big difference in impact if the recurrence time would increase from once every 10 years to once every 5 years. The peak doubles, from 25 to 50 people not accepting the disruption. Not acceptance rates are predicted to shift between t=1 and t=6 from 0.73%-4.39% to 1.45%-8.73% which is indeed about twice as much. In inter/extrapolating the values of the valuation of recurrence times, the shift from 10 years to 5 years is bigger than the shift from 2 years to 1 year. This explains why the two climate change scenarios for the 18.9mm event and the 35.7mm event are so different, whereas in the current climate they are comparable.

When including the climate change scenarios the conclusion remains that the 35.7mm event happening once every 5 years will lead to the highest number of people not accepting the disruption (50 people). The 50mm rainfall event has the lowest impact, which is in the current climate zero people, and in a changing climate 4 people.

However, the impact is largely depending on the effects of recurrence time. The effect of recurrence time was measured for 2 and 10 years. The effects for 1, 5, 25, and 50 years were inter/extrapolated assuming a linear relationship. The conclusions regarding comparison with climate change scenarios should be seen as illustrative and considered with caution.

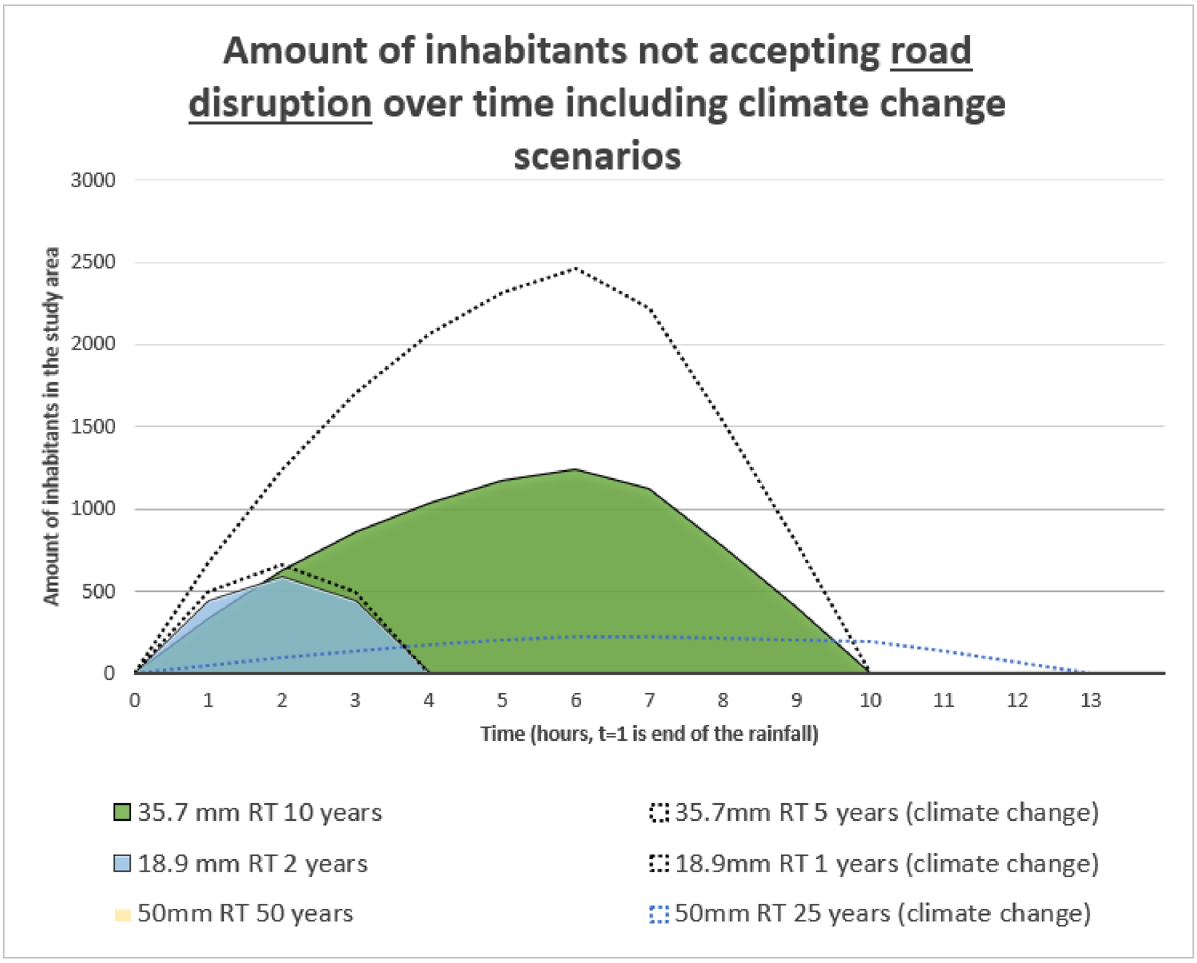

Figure 55: Amount of inhabitants not accepting road disruption over time including climate change scenarios.

The same type of graph is made for the impact of road network disruption. The total amount of affected people is a lot higher (see figure 55) then on the electricity network. The impact of the 35.7mm rainfall is clearly a lot higher than the 18.9 mm rainfall. This is in contrast with the differences in impact of the of rainfall events within the electricity network. Again, at t=1 the impact of the 19.8 mm rainfall is slightly higher, but at t=2 the 35.7mm event takes over and continues to increase until t=6. The peak of the 18.9mm rainfall event lies at t=2 with 585 people not accepting the disruption. The impact of the 35.9mm peaks at t=6 with 1243 people predicted to not accept the disruption. At t=7 the curve of the 35.7 mm rainfall seems to decrease linearly whereas it is expected to be a convex curve as before. However, from t=7 the not acceptance rate increases with much lower steps (see figure 55). The curve is convex but it is too small to notice.

The climate change scenarios are comparable to those of the electricity network. The 50mm rainfall has a very low impact with its current recurrence time (maximum of 4 people, not visible on the graph). With a changing recurrence time this increases to 227 people. Difference between the current and changing climate scenario for the 18.9mm rainfall is relatively small, a shift in peak from 585 to 663 people (net 78 people). However, the difference between the climate change scenario and current scenario for the 35.7mm event is big: a shift in peak from

1243 people to 2459 people (net 1,216 people). Again this is due to the different valuations of recurrence times.

Table 21: Maximum values of people not accepting disruption for different rainfall scenarios and networks.

	Maximum values people not accepting disruption	
Event	**Electricity network**	**Road network**
18.9mm, RT 2 years	23	585
18.9mm, RT 1 year (climate change)	26	663
35.7mm, RT 10 years	25	1243
35.7mm, RT 5 years (climate change)	50	2459
50mm, RT 50 years	0	6
50mm, RT 25 years (climate change)	4	227

The maximum values of people not accepting the disruption between the networks can be compared. Unsurprisingly disruption of the road network leads to much more people not accepting the disruption than the electricity network. A conclusion is thus that measures reducing the impact of road network disruption are effective to reduce the number of people not accepting disruption due to heavy rainfall.

6.3.3 No acceptance for disruption – different socio-demographic scenarios

The method also allows to predict how many people would not accept given disruptions taking into account different socio-demographic characteristics. This is especially interesting when it is known what the characteristics are of the people living in the neighbourhoods which are affected. This section gives insight in how these differences influence the number of people not accepting the disruption.

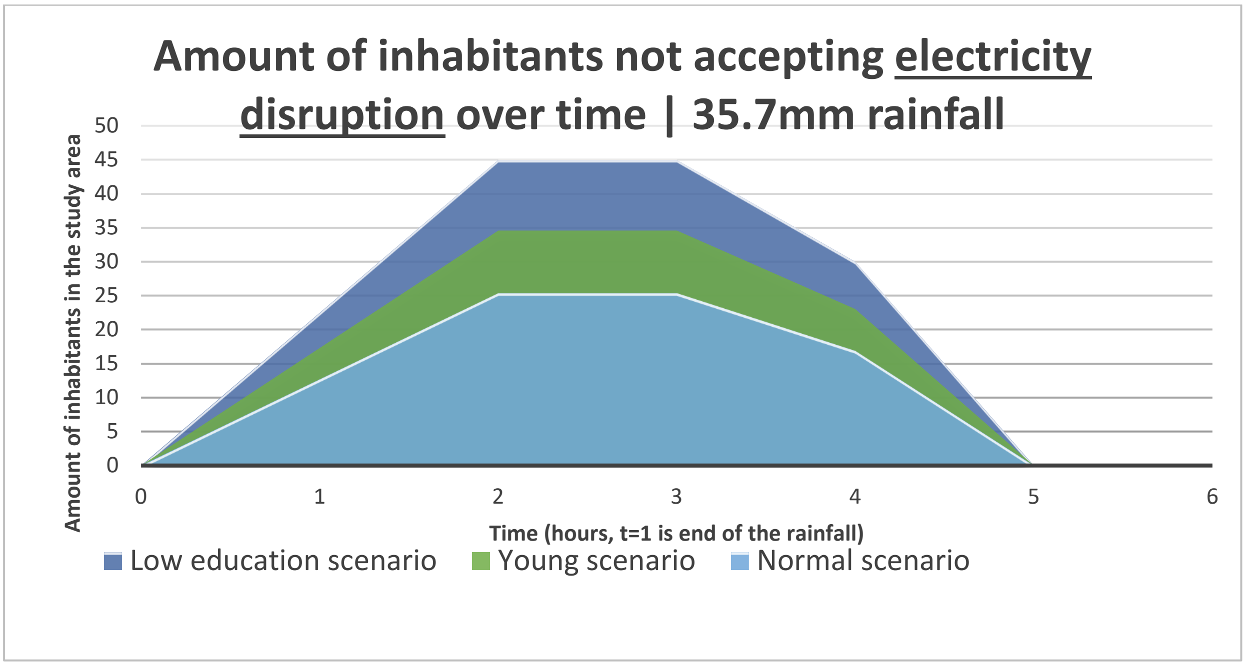

Figure 56: Number of inhabitants not accepting electricity outage with different socio-demographic scenarios.

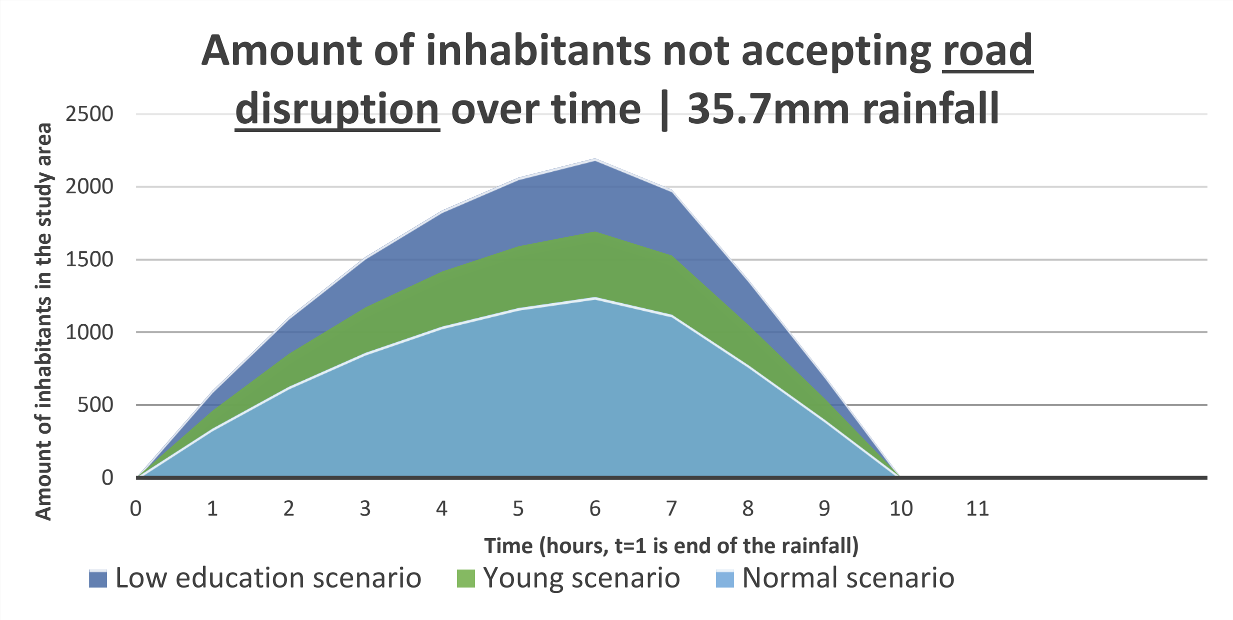

Figure 57: Amount of inhabitants not accepting electricity outage with different socio-demographic scenarios.

Table 22: Maximum values of people not accepting disruption for different socio-demographic scenarios for rainfall 35.7mm.

	Maximum values people not accepting disruption	
Event - Time (hours)	**Electricity network**	**Road network**
Normal/base scenario	25	1243
Low education scenario	45	2197
Young scenario	35	1693

Three scenarios are compared: the base scenario, a *low education* scenario and a *young* scenario. In the base scenario the reference categories are chosen to be the largest group in the sample. The categories high education and age group 60-69 are the reference groups. *In* chapter 5 is concluded that the younger people are, the less tolerant they are to critical infrastructure disruption. This section provides the *young* scenario where the average inhabitant is 18-29 years old, instead of the reference scenario of 60-69 years. The estimates in chapter 5 show that the odds that a person between 18-29 years will not accept the disruption is roughly 1.4 compared to the reference category. The second scenario takes low educated people as the standard instead of high educated. The chance that a person with low education will not accept disruption is 1.8 times higher compared to high educated people.

These differences are visible when comparing the three scenarios in figure 56 and 57. Values of the figures are presented in Appendix N. The shape of the scenarios are the same, the blue areas of figure 54 and 55 from the previous section). However, the height varies because the valuation of disruption varies per scenario. As expected, the maximum number of people not accepting disruption is the highest in the *low education* scenarios (for electricity disruption 45 people; road network disruption 2197 people). This is as expected 1.8 times higher than the *base* scenario. The maximum number of people not accepting the disruptions in the *young* scenario are 35 people for electricity outage and 1693 for network disruption. This is as expected about 1.4 times the amount compared to the *base* scenario.

The scenarios illustrate the importance of knowing the characteristics of the infrastructure user. They show the potential to incorporate different sociodemographic characteristics in the predictions and the influence this has.

6.3.4 Input to set a norm for the desired level of resilience

In order to conclude if the established number of people not accepting the predicted disruptions --and to be able to conclude if the networks are resilient enough—a norm or standard is necessary. The literature research elaborates on the current practice in norm setting. The norm is set using the As-Low-As-Reasonable-Possible approach, usually with a lower and upper bound. In the Netherlands the acceptable norm for an individual to drown in a flood is set to a maximum of 1 person per 100,000 person per year (commonly written as a safety standard of 10^{-5}). Of course there chance a person drowns cannot directly be compared with the chance a person will *not accept disruption.* The norms should be different, but the same method could be used.

The current level of resilience of the electricity network gives a maximum of 25 people not accepting the disruption. For a population of 176,000 this results in a ratio of 0.00014 which complies with a safety standard in the order of magnitude between 10^{-3} and 10^{-4}. For the road network the maximum number of people not accepting the disruption due to flooding was 1243. In comparison to all inhabitants it is a ratio of 0.007 which complies with a safety standard between 10^{-2} and 10^{-3}.

It is the role of politicians to establish the acceptable norm by evaluating what is technically possible and acceptable while remaining cost effective. But other factors play a role as well. For example direct damage to the networks, image loss or sustainability considerations. This research evaluates the current level of resilience to fall around a 10^{-3} norm. If this would be the norm, it would mean that it is acceptable that 1 out of 1000 inhabitants may be confronted with a disruption that the individual would not accept. The norm could function as the desired level of resilience which should be compared with the current level of resilience to evaluate if the networks are resilient enough. However, as shown in the framework proposed in the introduction of this research, a desired level of resilience can only be established when taking into account the costs of measures. Moreover, since this research carried out only in one small case study area, it can only serve as a starting point for further research on what a norm could be.

6.3.5 Input to selecting effective measures

The results of chapter 4 already indicated that the disruption of the road network leads to the highest amount of affected people compared to the electricity network. In this case study also the valuation of this disruption is taken into account. Then still the disruption of the road network is predicted to lead to the highest number of people not accepting the disruption. It is thus advised to select resilience improving measures to improve the road network rather than the electricity network. However, this comparison only takes into account the direct effects of the hazard. Possible cascading effects are neglected. Resilience improving measures (for example increasing infiltration capacity or installing extra pumps in tunnels) are highlighted in chapter four and in the literature review.

When applying the framework from figure 1 to the obtained results, and if it can be concluded that the desired level of resilience is not far from the current level of resilience, this gives input for the type of measures which should be evaluated. For example, investing in expensive measures such as renewing the sewage system to increase capacity might be very effective but not necessary because it will result in an overly resilient system. Less costly measures, possibly investing in hazard awareness campaigns, might be sufficient to balance the current and desired level of resilience more efficiently.

Moreover this research highlights that proposing measures to increase the resilience of the users, and thereby increasing acceptance levels of infrastructure disruption, is also effective. If users are prepared for certain hazard they will probably accept longer durations of disruption. This can be as simple as having an emergency kit with candles, food and water at home in case of electricity outage. Petersen, Lundin, et al. (2020) suggest that information provision during a crisis can also lead to higher acceptance levels, as well as being able to provide a minimum service level.

6.4 Conclusion and discussion

This chapter demonstrates a method how the current and accepted level of resilience from the previous chapters can be combined. First the resilience triangles with acceptance levels are presented as a visualization of the method. Then the focus shifts to the maximum number of people not accepting disruptions given different scenarios.

In the current climate, the base case of this research, the 18.9 mm rainfall event (recurrence time 2 years) and the 35.7mm rainfall event (recurrence time 10 years) lead to a comparable number of people not accepting the electricity disruption (respectively 23 and 25 people in the study area). Taking climate change into account and increasing recurrence times, the 35.7mm rainfall leads to the most people not accepting the disruption (50 people).

The road network impacts about 20 times as many people as the electricity network. Thus also without including acceptance levels it seems trivial that the road network leads to more people not accepting the disruption. In contrast to the electricity disruption, there is a big difference in people not accepting the disruption between the 18.9mm rainfall and the 35.7mm: respectively 585 people and 1243 people. This can largely be explained by the differences in duration of disruption. The difference in duration of the events is larger for the road network (6 hours) then for the electricity network (1 hour).

Socio-demographic characteristics have a large influence on the acceptance of disruption. A scenario with the inhabitants in the age category of 18-29 leads to 1.4 more people not accepting the disruption. If the inhabitants would be low educated instead of high educated the number increase with a factor 1.8. This emphasizes the importance of knowing the user of the infrastructure. This is in line with research from Petersen et al., (2018). The authors recommend critical infrastructure operators to research who their users are and what their preferences are in relation to disruption of the service.

6.5 Limitations

Uncertainties in the outcomes originate primarily from the input data. Specifically for this chapter these are 1) the estimates regarding the effects of recurrence time parameters; 2) interpolation of the not-acceptance rates between t=0 and t=6. More research on the valuation of recurrence times and duration of disruption is needed to get accurate results. Other limitations to the input data is elaborated on in chapter 4 and 5.

Regarding the method the main limitation is that cascading effects are not taken into account. The infrastructure is evaluated as a separate system. However, as mentioned in the literature review, critical infrastructures are always part of a system and should never be analysed separately (Rinaldi et al., 2001).

6.6 Recommendations

The method can be used to evaluate measures which reduce the duration and consequences of the event or which limit the number of people affected. The not-acceptance rate increases with the duration of the disruption, which highlights the importance to also include measures to support quick recovery after the event. However, this implies quantification of the impact of the measures. This can be used as input to the resilience triangles and allows to run different scenarios, as proposed by Murdock et al., (2018).

The method also has potential to zoom in on specific neighbourhoods where a lot of disruption is expected. This information is yet presented in chapter 4. If the socio-demographic characteristics of the inhabitants are known, these can be used to evaluate the risk of people actually moving to other parts because of potential disruption. When people with socio-demographic characteristics related to low acceptance levels are clustered in neighbourhoods with high chances of disruption, this might lead to degradation of the areas. Identification of these neighbourhoods is advised to prevent local migration. However, it must be noted that the influence of critical infrastructure disruption is not the only factor influencing if people would accept the consequences of flooding. It is often a sum of multiple discomforts. For example water damage to houses might be perceived worse than disruption of any critical infrastructure network.

Overall the method presented in this chapter is potentially promising to include users preferences into the process of climate adaptation of critical infrastructures. As far as known it is the second framework in academic literature to do this. Hence more research to refine the method is recommended. This specific case study is carried out in an area with a limited history of disruptions of critical infrastructures in general, let alone due to flooding. On the one hand this leads to relative low risk of disruption. On the other hand it also makes it hard to measure when people will not accept certain disruption, because they have not experienced it before. A case study in an area with more risk of disruption and a population who has been exposed to hazards before is recommended to test the method. Also collaborations with critical infrastructure providers or municipalities is recommended to evaluate the practical usefulness of the method.

7. Conclusion

The resilience of critical infrastructures has been put under increased pressure in recent decades by both urbanisation and climate change. To answer the question how this resilience can be secured now and in the future, first more fundamental questions were needed to be answered. What is resilient, and what is resilient *enough*? This study proposes a framework, presented in figure 1, and introduces the concept of the *desired level of resilience*. This is a level or norm with which the *current level of resilience* can be compared using predefined criteria. The current level can be obtained by carrying out a resilience assessment. Comparison of the two will lead to insight how measures can be effectively proposed and assessed, which will lead to a new *current level of resilience.*

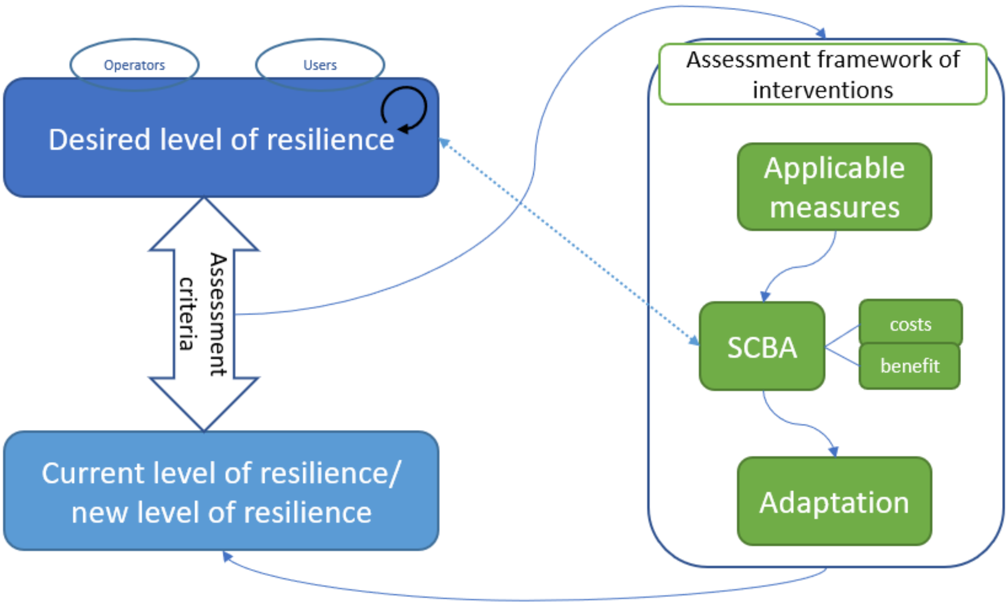

Figure 1[copied from page 20]: Framework for improving resilience by taking into account the desired level (Bles et al., 2020)

This research offers a method to quantify this *current level of resilience*, and proposes the right assessment criteria to include the users' perspective. The resilience assessment thus includes the users' resilience as well. The method is tested in a case study in the Hague, The Netherlands.

The research starts by exploring the state of the art literature regarding critical infrastructure resilience. An important shift is observed in defining critical infrastructure resilience. Whereas it used to describe the asset which is delivering the essential service or good, it is now emphasised to focus on the critical service it provides, which should be protected. Moreover, this shift includes accepting that the vital functions cannot be protected to all types and severities of hazards. This calls for the development of theory on what the desired level of resilience should be. Such a standard can only be set when the resilience assessment is quantified. A commonly used method is to draw resilience triangles. The system's functioning is then set out over the time before, during and after a hazard. Research within the IMPROVER project proposes to use tolerance triangles (Petersen et al., 2019; Petersen, Fallou, Carreira, et al., 2018; Petersen, Lundin, et al., 2020). These triangles set out the tolerance towards critical infrastructure disruption over the duration of the disruption. Hence, the resilience triangle and the tolerance triangle can be compared, as if to compare *the current level* and the *desired level* with each other. The research is one of the first in its' field and thus the authors call to expand the research in this field with new methods and frameworks to include users' perspectives in resilience assessment. The research carried out in this graduation project aims to contribute to that call.

Within this research, a slightly different approach is taken. The proposed method consists of three steps to include the users' tolerance levels in the resilience assessment.

1. The first step is the resilience assessment, which aims to quantify resilience in terms of *number of people affected by the disruption.* This involves a simulation of different rainfalls in a 3Di hydrodynamic model, which produces inundation maps. These maps are then analysed in QGIS by comparing them with spatial data of the critical infrastructure systems and population densities.
2. The second step analyses the users' acceptance levels to disruption, which can also be considered as the resilience of the user. This is quantified in the *share of people who do not accept a posed disruption.* This is done in a questionnaire-based approach using ordinal regression to analyse the data.
3. The final step combines the outcomes of the previous steps and establishes the *number of people unwilling to accept disruption.* Dimensions included in this assessment are 1) severity of hazards; 2) recurrence time of hazards; 3) types of critical infrastructures network; 4) number of people affected over time and 5) acceptance levels to disruption over time.

7.1 Findings case study

7.1.1 Part I Resilience assessment

Within the case study area, five critical infrastructure networks were assessed: the road network, the electricity network, the mobile network and the accessibility of supermarkets and the hospital HMC Westeinde. The first two networks were used for the quantification of resilience. The number of people affected by the disruption of the network is calculated for different rainfall events with different predicted recurrence times. The results are presented in resilience triangles, which show the disruption over time. The calculations show that the number of people affected by electricity outage is estimated to be relatively low compared to the number of people affected by road network disruption. For a rainfall of 18.9mm in one hour, which has a recurrence time of two years, 808 and 18,330 people are affected respectively (0.46% and 10.40% respectively). A rainfall of 35.7 mm in one hour, predicted to happen once every ten years, leads to 1733 people (0.98%) affected by electricity outage and 41,330 people (23.44%) affected by road network disruption.

The mobile network will not be affected by the rainfalls. Furthermore it is unlikely that the area around the hospital HMC Westeinde will be flooded, nor will the electricity fail. However, the accessibility of the hospital will be reduced due to the flooding of important access roads. The accessibility of supermarkets is not significantly affected by flooding either. Only a limited number of the grocery stores is predicted to close due to flooding or electricity outage. These are all located in areas with a redundant number of other supermarkets.

7.1.2 Part II Acceptance levels to disruption

An analysis of the questionnaires show that the acceptance of disruption is relatively high. Users were asked to evaluate the trade-off between accepting the disruption or moving somewhere else due to unacceptable levels of disruption. Disruption of the electricity network was found to have the strongest influence on acceptance levels. Some socio-demographic characteristics were included. Findings showed that lower education levels are related to lower acceptance levels to disruption. Furthermore, younger people tend to accept the disruption of critical infrastructures less than older people.

7.1.3 Part III Including the users' tolerance levels in the resilience assessment

The combined results of the resilience assessment with the acceptance levels are visualised in acceptance triangles. The maximum number of people who do not accept the disruption after a certain duration is used to define the number of people unwilling to accept disruption of a particular network. For both networks, the 35.7mm rainfall event turned out to cause the highest level of unaccepted disruption. Electricity disruption would lead to a maximum of 25 people (0.014%) regarding the disruption as unacceptable. Road network disruption would lead to 1,243 people (0.70%) unwilling to accept the disruption. Scenarios with different socio-demographic characteristics of the population and increasing recurrence times are presented as well.

7.1.4 Application of the proposed framework

If one could conclude that the current level of risk and resilience in the study area is generally accepted, the percentages (0.014% and 0.70%) of people unwilling to accept posed disruption could serve as an input to what the order of magnitude could be for the *desired level of resilience*. The lower the number, the higher the norm. However, according to the proposed framework, determining the desired level or resilience also entails an evaluation of costs of measures as well. Next to that other factors such as direct damage to the infrastructures will obviously play a role as well. Hence, this research should be regarded as an indication of how the desired level could be established. Furthermore, deciding what is acceptable and what is not, is a political question to which research can only give input but no final answers.

This method demonstrates that the number of people who refuse to accept the disruption can be lowered by either increasing resilience of the critical infrastructures, or increasing the resilience of the infrastructure users. The former approach leads to measures related to flood mitigation, such as increasing infiltration or increasing robustness and redundancy of the networks. The latter strategy would aim to increase acceptance levels to disruption. One way of achieving this is preparing inhabitants of an area prone to flooding for the possible consequences.

When applying the framework from figure 1 to the obtained results, and if it can be concluded that the desired level of resilience is not far from the current level of resilience, this gives input for the type of measures which should be evaluated. For example, investing in expensive measures such as renewing the sewage system to increase capacity might be very effective to reduce flooding, but may not be necessary. It might result in a system which is more resilient than needed. Less costly measures, possibly investing in hazard awareness campaigns, might be sufficient to balance the current and desired level of resilience more efficiently.

7.2 Recommendations to improve the case study

This type of research is relatively new in its field. With only a few pilot studies to build on, this study should be regarded as a test case. A full reflection on the separate parts is presented at the end of each chapter and main point are summed below.

The resilience assessment of the city centre of The Hague offers a suitable method. The main point of improvements are:

- The case study area was relatively small. This led to complications in the 3Di model which was used for the flood simulations. Simulating a larger area will probably lead to more realistic results.
- The quantification in terms of people affected over time proves to be a good method. However, quantification was only carried out for the direct effects of two networks. Expanding the assessment to include all relevant networks and including cascading effects in the quantification is advised.
- The way the number of people affected by road network disruption needs improvement as the quality of digital maps is suboptimal. Analysis of the critical roads in the network in combination with a greater study area including origin destination data would be a good start.
- Whether or not an electricity box will flood depends heavily on the physical environment on the local scale. These elements cannot be represented fully in the 3Di model. It is thus recommended to site-visit the electricity boxes which are indicated in this research as vulnerable.

A questionnaire-based approach is proved applicable to measure users' preference levels. The following points of improvement are:

- The presented scenarios in the questionnaire did not match entirely with the actual risk of disruption. The levels of variables for disruption of the road and electricity network ranged between six hours and two days. Though, in the infrastructure resilience assessment was found that with those corresponding rainfall events the disruption is limited, and the networks have recovered mainly after six hours. Carrying out the resilience assessment of the infrastructures before composing the questionnaire is advised. This will make sure that scenarios can be composed which are realistic consequences of hazardous events in the area.
- The variation in the duration of disruption and recurrence times were limited. Hence, assumptions were made in order to inter- and extrapolate effects. It is recommended to include a larger variation of the duration of disruption as well as recurrence times to validate these assumptions.
- The set-up of this experiment did not allow for measuring interaction effects between disruption levels of infrastructures. Especially when cascading effects are to be expected in the resilience assessment, it is advised to include these interaction effects.

Taking these suggestions into account the case study is replicable in other areas. Other software tools to make rainfall simulations, like Tygron, can be used as well. For quick analysis of the flood risk a digital elevation map might even suffice to indicate vulnerable areas. The acceptance levels can be measured using the questionnaire template of this case study with adjusted variables and levels. If an area is assessed which is comparable to The Hague, for example urbanized areas is the west of the Netherlands, the tolerance levels of this research might even be used. Since, differences in socio-demographic characteristics are taken into account in this analysis. However, as research is lacking on what factors influence tolerance levels, it would be better to collect data on this as well.

7.3 Recommendations for further research

The expected amount of disruption in the research area is limited, which is good news for the municipality. However, it is advised to carry out similar studies in areas with more severe hazards and a population that has actually been exposed to disruption. For example, the east coast of the United States is prone to flooding due to hurricanes. Also in Sidney, Australia, recent floods lead to substantial disruptions for longer durations. Studying the tolerance levels of the inhabitants of those areas gives better insight in the trade-offs. Comparing the case studies might give insight into what unacceptable situations are, leading to better understanding of the desired level of resilience.

Next to that, additional research is recommended how to include the users’ perspective in the resilience analysis. Different approaches to measuring acceptance levels and including different dimensions is necessary. This research only includes different durations of disruptions, but does not assess alternative services during a disruption. For example, the acceptance of extra travel times during road disruption could be included. Research on what a minimal level of service should be, or what alternatives are preferred during a hazard is recommended. Also, this study measured acceptance levels to disruption as a trade-off to moving to another location. Another option could be to monetarize resilience improving measures and let users chose what they prefer.

This study only touches briefly upon how both the resilience of networks and that of users could be increased. Especially the latter should be given more attention. Preparing communities to possible disruption seems a no-regret strategy. More insight in what factors determine if a hazard is acceptable or not is necessary. A case study, including areas where the population has experienced hazards, seems an appropriate method.

Lastly, an application of the full framework would be an interesting research project. This research specifically focusses on the *current level of resilience*, gives input to what the *desired level of resilience* could be and illustrates briefly what this would mean for the assessment of measures. Completing the full cycle in detail and especially including the quantification of costs and benefits of different measures would be beneficial to validate this framework and put it in practice.

7.4 Academic relevance

This research adds to existing research on resilience of critical infrastructures in several ways. Firstly, the proposed framework reveals a new perspective to assess resilience and propose effective measures. This adds to the limited literature base on methodologies regarding the process of attaining resilient systems of critical infrastructures.

Secondly, the quantification of the resilience of critical infrastructure networks is not an established practice. Previous studies propose a limited variety methods and metrics. This research choses to present the resilience of the infrastructures in resilience triangles. Also, the use of hydrodynamic modelling of the rainfalls improves the accuracy of estimations.

Thirdly, the research by (Petersen, Fallou, Carreira, et al., 2018) identified the *desired level of resilience* as the median of the chosen answers as to what duration of disruption is acceptable. However there is no trade-off within this decision process. Hence, this research aims to improve on that by making the users evaluate an alternative: moving to a different living environment. Also, data from questionnaires is analysed using ordinal regression, which lead to the added insight in effects of different socio-demographic features, differences in evaluations of different networks and the valuation of recurrence times of events. Research on valuation of recurrence times is unique in this field.

Lastly, including the resilience of the user and the networks in combined resilience-acceptance triangles is a new method and proposes a new metric *number of people unwilling to accept posed disruption.* This gives input in exploring what the order of magnitude of the desired level could be.

7.5 Implications for practitioners

Network operators are advised to include the users' perspective in their resilience assessment. This research shows differences in socio-demographic characteristics which indicates that different needs for different customers is demanded. When analysing the impact of disruption to the network, try to quantify this in terms of people. Also, take into account the duration of the disruption, since this has proven to be of significant influence to the tolerance. Look at your disruption as to what impact it has to the infrastructure user and how can this situation become less uncomfortable to the user?

Municipalities is advised to include analysis of vulnerabilities of the electricity network specifically. Because, due to the combination of possible cascading effects and high influence to tolerance levels of the user, the disruption of this network is critical. The method proposed in this research proves to be simple but effective, especially when combined with a site-visit. If network operators renew their electricity boxes anyway, raising the boxes is probably a cheap but efficient measure.

In general it is advised to all practitioners concerned with critical infrastructure resilience to include measures which increase the resilience of the users to the list of possible measures. These measures might be more effective in reducing unwilling disruption than increasing the resilience of the infrastructure assets themselves.

Lastly, there is no established norm yet regarding critical infrastructure resilience. When setting out a climate adaptation strategy, add the step to establish a certain ambition: the desired level of resilience. This will give direction to the evaluation process to select measures.

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Appendices

Appendix A Height map of the study area

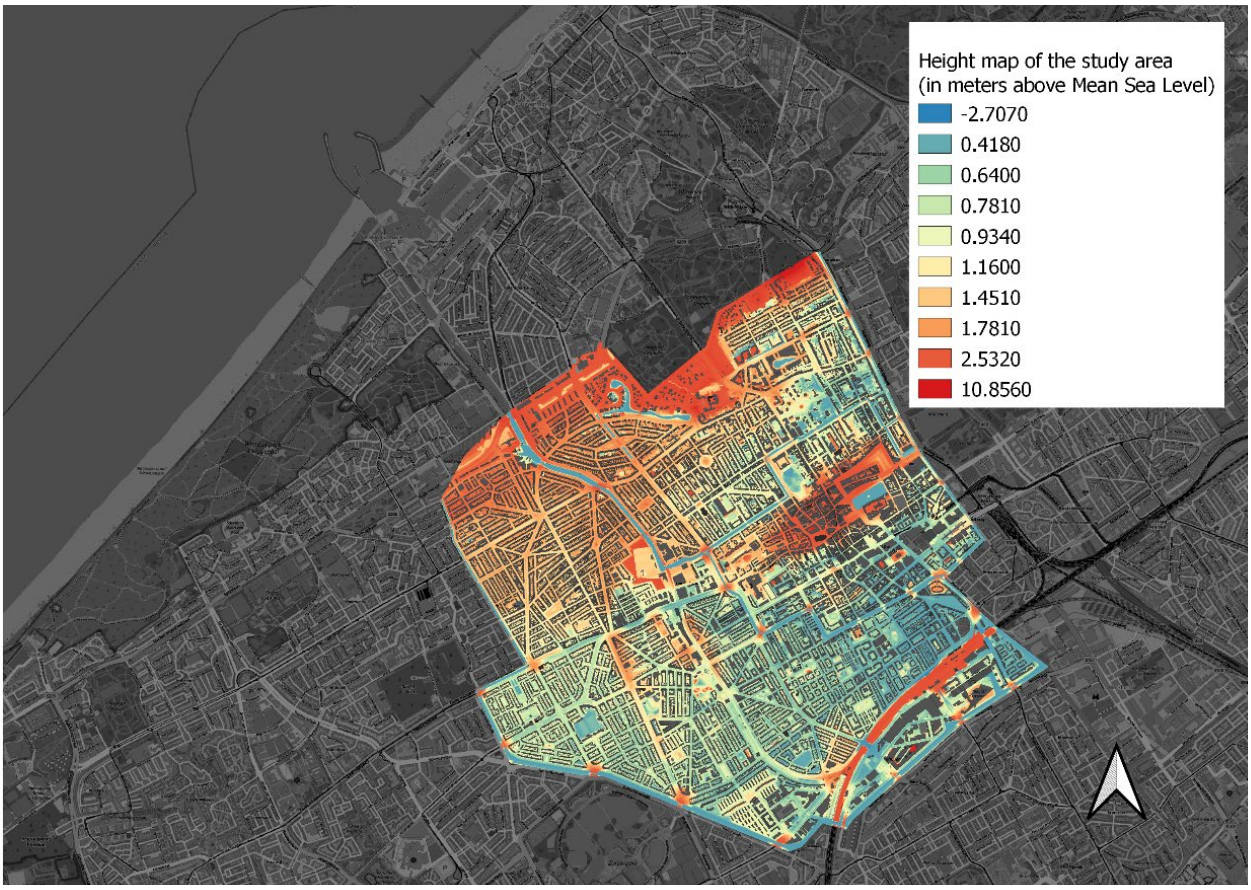

Figure A-I: Height map of the study area.

Appendix B Location of mobile network antennas in the study area.

Most antennas are located on top of buildings on a height between 20-30 meters. Hence, these antennas will not flood due to heavy rains. (Antennekaart.nl, n.d.). Figure B-I and B-II show the antenna density in the study area. Figure B-I shows a close up of the study area, Figure B-II the whole region, and Figure B-III the coverage area of the mobile phone network. From these maps the redundancy in the mobile network is concluded.

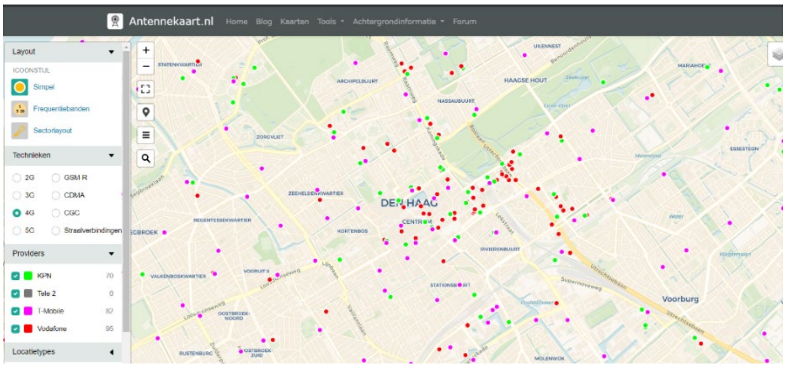

Figure B-I: Map with antennas in study area (Antennekaart.nl, n.d.).

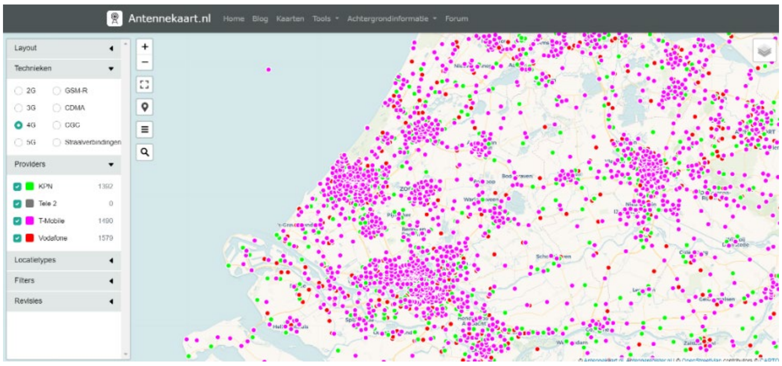

Figure B-II: Map with antennas in region of study area (Antennekaart.nl, n.d.).

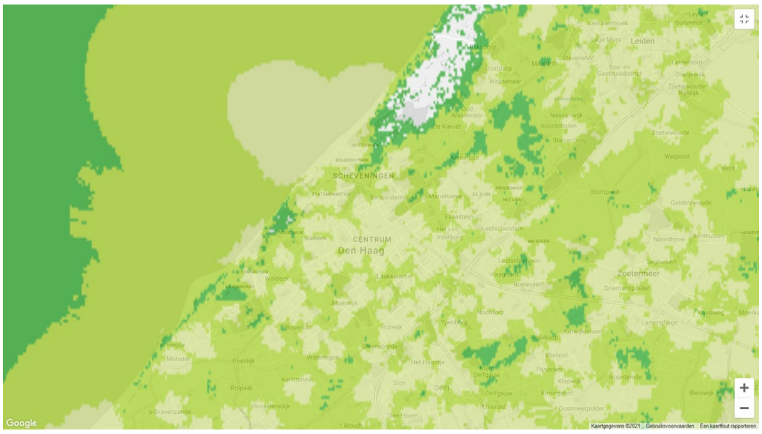

Figure B-III: Map of mobile network coverage of provider KPN in the region of study area (KPN, n.d.).

Appendix C Validation of results with Tygron model

Tygron is another software tool which can be used to simulate rainfall and model floods. This software is used by van Rijn (2021) as part of a to be published masters' thesis on flooding in The Hague, with a focus on the area around the Huygens Park. Figures C-I and C-II show the inundation after a 50mm and 70mm rainfall event of one hour. It shows the same inundation patterns as retrieved with the 3Di software. The most vulnerable areas remain the *stationsweg* and the *Prins Bernhardviaduct*, which have comparable predicted water depths.

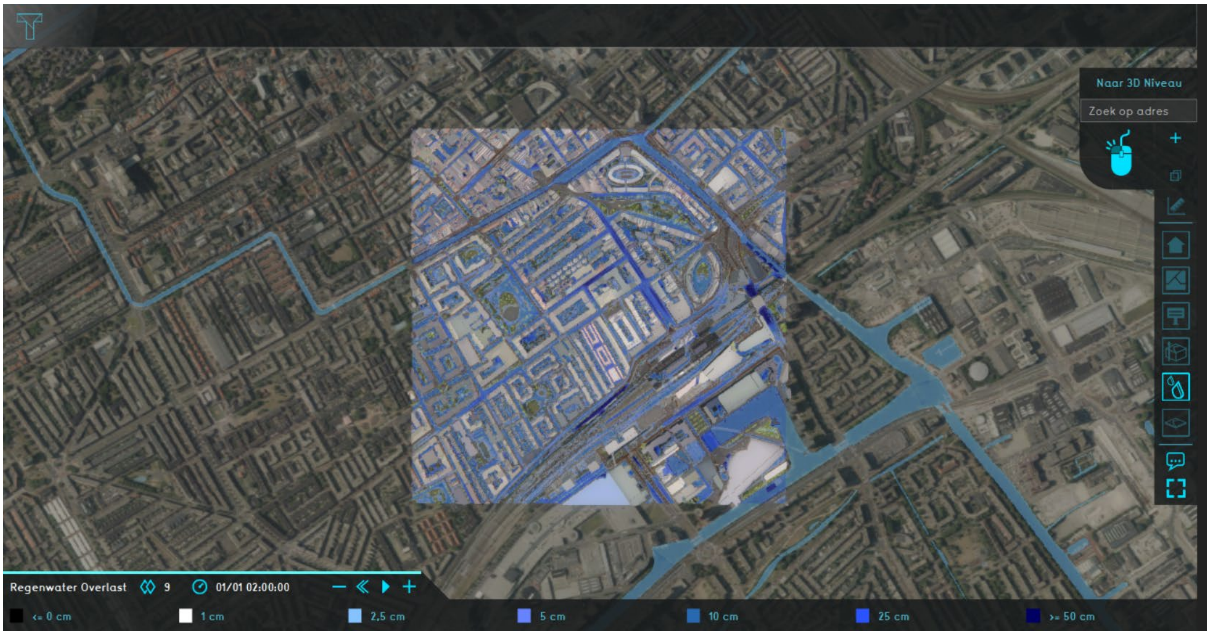

Figure C-I: Inundation map of a 50mm rainfall event simulated in Tygron (van Rijn, 2021).

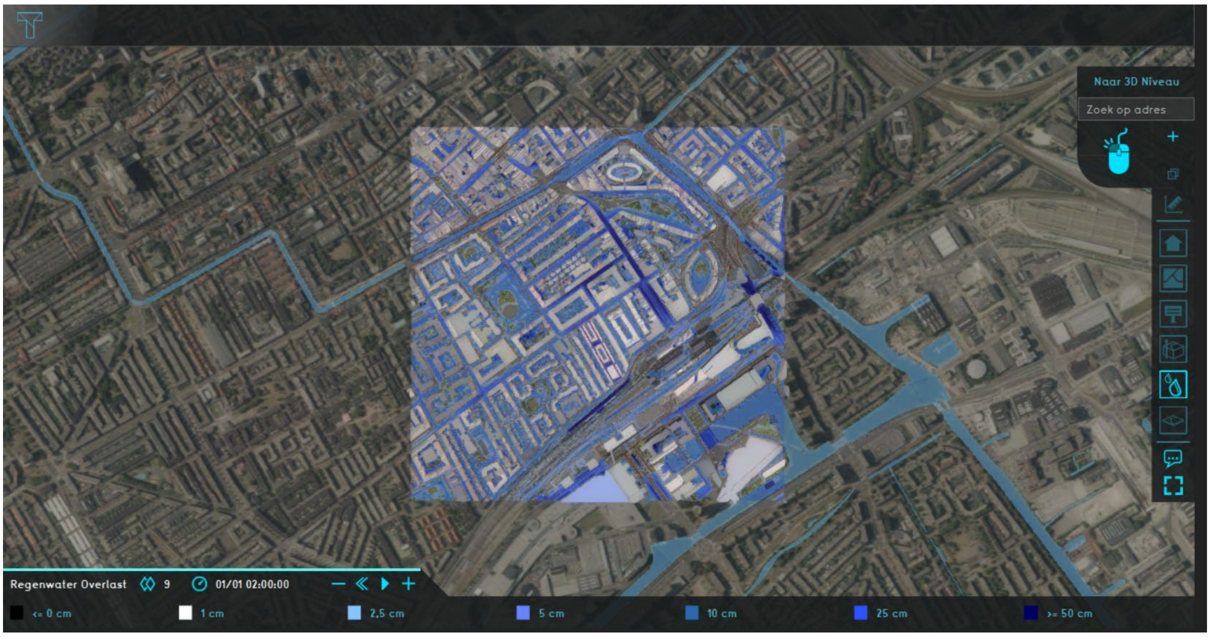

Figure C-II: Inundation map after a 70mm rainfall event simulated in Tygron (van Rijn, 2021).

Appendix D Interview validation results road network

Interview with an expert of the department of *Sewage system, Soil and Roads*, Municipality of The Hague.

Date: 13/4/2021

Discuss results 3Di model and consequences for the city.

Do you find the water depth maps coming from the 3Di software realistic?

In general, the vulnerabilities you see in the results correspond to whatever is experienced. The tunnel at Vaillantlaan has flooded 4 times in 20 years, of which once even now a new pump has been installed. However, with this new pump it is not to be expected that the tunnel will flood over one meter every two years. That does not seem realistic. Maybe it is realistic that a rainfall happening once in 10 years will cause 1 meter of water.

The tram tunnel that is flooded is not in charge of the municipality, but it seems as if a wall is not properly placed the height map. That wall ensures that water does not flow directly into that tunnel, because as far as is known, that tunnel never fills with rain.

The tunnel at the Rijswijkseweg is sometimes flooded, and perhaps indeed impassable once in 10 years.

The water depths at Loonduinseweg also seem a bit extreme. The expert can not remember that traffic was blocked by heavy rainfall on that road. When we check the infiltration map and the altitude map, we do not observe any strange values. But perhaps it is due to an underestimation of the water storage capacity of the tramway. We wonder aloud if the overflow of the sewer under the road is modelled in the right way, but we cannot check that now. However it would be weird if the sewer was not present in the model because the municipality provided the data for the model to Nelen and Schuurmans. The street is low-lying and used to be a canal. Water does stay there during a flood, but these depths have not been observed before.

The water on the roads in the neighborhoods Transvaal and Schildersbuurt and at the north side at the Zeeheldenkwartier and Regentessekwartier is valid. Also the neighborhood Stationsbuurt is a vulnerable area which collects a lot of water during rains. The sewage overflow does not work very well there. The area is completely dependent on pumps (in the future it may have to be closed off from the main sewer network). Flooding in this area is mainly a problem for residents. There is no critical infrastructure running through the area (roads).

In general, the results for the 1x in 2 years rainfalls seem a bit extreme, and that would go more towards the 1x in 10 years rainfalls. On the other hand, it may be possible that the water depth maps are correct, but that there is indeed so much water for a very short time, so that this is not noticed as such. Also, the rainfall has now been modelled so that all rain falls in the city centre, but it has never happened that so much water fell in the entire area at the same time for such a duration. It happened only in parts of the city, especially in Scheveningen near the sea. In that area there were showers of 40mm.

We cannot think of any errors in the model. Only the fact that the elevation map is quite rough, because small thresholds and ledges have a lot of influence on where the flood occurs exactly. The micro-effects therefore matter a great deal. With such a model, it therefore remains difficult to predict exactly where how much will flood.

How realistic do you think the disturbance is for the residents of the city? Looking at the failure of the road network, and the impact this has on people?

In practice, people do stay indoors when it rains heavy. It may well be that about 10% of the inhabitants are possibly affected by a rainfall that occurs once every 2 years. But this does depend on whether the resident wants to go somewhere, or just stay home and go shopping an hour later. You would almost make a sociologist look at behaviour change because of a rainfall. Of course, if it rains at night, it's not a problem. So you look at the *worst case* scenario when you say that 10% suffer from it. But it is an area with high density and a lot of traffic flows, so the impact is great.

The greatest danger arises if something else happens during such a storm and the emergency services are unable to get there. For example, due to severe weather, hail and wind and the fact that trees are blown down or things are on fire and that the fire brigade cannot get there.

On what standards does the municipality base its policy?

The norm is that there must be no more water on the street for more than 45 minutes, which cannot be discharged through the sewer. This is calculated with rainfall design 8 (formerly rainfall design 7) which has a recurrence time of two years. If we look at the results, then the tunnels would not meet that, but that seems unrealistic. On the Loonduinseweg there is a lot of water, but it is possible that for the design rainfall 8, this will be drained within 45 minutes. It probably falls within the norm.

What are typical measures that can remedy these disorders?

In acute problems, we first look at how we can drain the water better. For example, by placing a sewer overflow. An additional underpass (sewer pipe) so that the water is diverted differently or larger pumps and additional pumps are among the possibilities. Or extra buffer capacity underground. Sometimes you also see that the pumps capacity is high enough but that the pressure line is too small, or disturbed.

If it is structurally a problem, you can also save water by placing crates where water can run in, which later infiltrates the bottom. This is not possible at all soils, and if the groundwater level is too high it also does not make sense (for example in the station area).

In addition, you can increase the infiltration. You can also lower the plant holes and green strips (10cm), they should do this on the loose dune road, for example, so that the water can then run into the grass and the tree holes. Here they are now placed 20cm higher. Road hardening can be adjusted so that water can pass through.

At home level, an extra threshold or gutter also works well. An extra well is also sometimes done, but this is more for light showers. During heavy rains, you will see that water comes out and ends up on the street, in low-lying areas. So sometimes you want the areas not to be connected to the sewer network, because during heavy rains the water then rises from the sewer.

In general, it requires a lot of customization. There have also been occasional talks with HTM (tram company), to store water under the tram tracks and making a water draining tramway.

In climate adaptation, we look at three steps: water retention – water storage – water drainage. For acute problems, we are looking at increasing the discharge capacity. Less acute problems can be structurally adjusted by increasing retention, drainage and storage capacity.

In addition, of course, we are looking now looking at improving the resilience of the city surface and roads, but we could also look at making the residents more resilient to disruption. Finally, you can also make the infrastructures more resilient. Maybe electric boxes can just be plugged underground?

Appendix E Interview validation results Electricity network

Interview with the Risk Analyst of Stedin. Stedin is the network operator in The Hague.

Date: 12/4/2021

Discuss the results of the research on power outages in the study area of The Hague.

In this analysis the medium and low voltage stations, obtained via the Stedin website are used. Also the failing threshold value of 30cm is used. Are these correct assumptions?

0.4kV is a low voltage station, 10kV-0.4kV are the medium voltage stations. The medium voltage stations also include a transformer, which converts the 10kV voltage to 0.4, which then goes to the low voltage boxes. It's hard to say what exactly the failure height of the cabinets is. Each box is just a little different, some still function with 50cm water in it. In the past the used threshold was indeed 25-30cm, and in the current predictions as well, so the threshold value is valid. But we think that the actual threshold value is higher. A study is now being carried out which looks at what happens when a box floods and what happens then. The new boxes that are now being installed have a 'first phase fuse' around 50cm. If this makes a short circuit with the fuse below (10-20cm, for street lighting, bus shelters and traffic lights), then the fuse will burn out and the households connected to that first phase will have no power. Some households are connected to different phases, so they may have partial failure. In short, the failure height is difficult to estimate, 30cm is used but this is certainly on the cautious side.

Have you ever had a failure of an electrical cabinet due to water nuisance ?

It rarely happens. The expert remembers one case in their care area 4 years ago where a box was located near a viaduct that flooded. Two streets, about 70 households were then without electricity for a few hours. He knows from colleagues in Zeeland that it has happened there once too.

There are more than 1000 disruptions in the low-voltage network every year, so one such situation is very rare. Hence, the risk of electricity outage due to flooding is low.

What happens when such a box floods?

There is no redundancy in the low-voltage network (only due to changes in the network), so a mechanic must come. A mechanic must be able to arrive on site, so the road must be passable and the mechanic must be able to work under reasonable conditions (i.e. not in the middle of a hailstorm). If the water is drained from the street, an aggregate can be placed that takes over the function of the power box. It is also possible to choose to switch things 'in the net', so that the households get electricity again via a different supply. The repair of the box takes place within 1 or 2 days. It is part of the day service of the mechanics.

What do you think of the method for predicting the dropouts, given that you know which boxes will drop out?

It's a good estimate, an elegant method. When houses are connected to electricity, the shortest route to lay cables is always chosen. Feeding areas can thus be approximated in this way. The location of the cables of the electricity grid has not been included, but this is not bad because everything that is underground can withstand water, and there is in principle no redundancy in the low-voltage grid.

So the question is mainly whether the dropout of the boxes is well predicted?

Given the fact that we have not seen a lot of electricity outage due to heavy weather in the past, it looks like an overestimation. It may also be that there is regularly 30cm of water on the street for a short time, but that the boxes can withstand that. It still depends on a few factors. Rainwater is relatively 'clean', at least it is not salty. Salt water conducts better and will cause a short circuit sooner. It also depends on the time of day. If a small current flows between the two fuses (due to the water level) during a peak load of the net, this can already cause the fuses to melt. But, if this happens during the night when the net is not in use, such a small stream will not cause a short circuit so quickly.

The connection to the lamppost, traffic lights and bus shelters is placed lower, maybe 10-20 cm. From this you will expect failure sooner. The connection in lantern poles themselves is usually higher, around 50-80 cm.

What measures could you take to protect your network from flooding?

We have a kind of box of 60cm that you can place under a box, so that this box is higher and therefore resistant to a flood of 60cm. These are only placed when the box itself is in need of replacement (the natural replacement moment). Placing it is as expensive as replacing the box completely. These elevation boxes are placed, for example, in places along a quay that can be submerged in a port area, for example. In Vlaardingen they are placed.

In addition, you can of course ask yourself if the box should be located in that place, or that the box may have to be in a place that is higher. But that is a decision the municipality has to make. A box waterproof design makes little sense, there must always be holes in it to let the cables go through, and they last for a relatively long time, decades, so they will not remain completely waterproof.

How do you consider investing in the electricity grid to reduce flooding?

For investing, we have a risk matrix that looks at the probability that a certain risk will occur and the investment costs. The risk reduction / cost is the cost effectiveness of the measure. We are therefore looking for measures with high cost-effectiveness. If you look at the risk of flooding due to dike breakthrough or severe weather, that risk is quite low, but the consequences are quite high. The measure to increase cabinets outside the 'natural replacement time' is relatively expensive. So that is not a very high cost effectiveness. So little is being invested to reduce the risk of natural disasters, due to the estimated low risk.

Excavation work causes most of the fallout. The chance of a box being set on fire or someone hitting it with a car it is greater than that it is gets flooded.

Then two more concrete situations: a rainfall causes 1-3 hours of water on the road, and will cause a short circuit in about 22 electrical boxes, 13,000 people are without electricity (shower 18.9mm, 1x every 2 years). How long does it take before the disturbance is resolved?

You have to wait for the shower and disturbance of the road network to be over until the mechanic can come to the location and do decent work there. Many mechanics also live in the area itself, so they can be on site quickly, then of course an aggregate still needs to be called out or the net has to be switched on manually. Once the mechanic is installing an aggregate, the disruption will be resolved within 1.5-2 hours. If there are 22 boxes, that may be many, but there are enough aggregates. In about 2-4 hours after the disturbance everyone will have power again.

And for the 35.7mm rainfall, which puts 33 boxes under water?

About the same, think of 2-4 hours after the mechanics can get back on track and do their job so that most households have electricity again.

Are there standards on which you base your acceptable amount of power outage?

There is legislation on how much power outage a customer may experience and how much compensation he receives for it. In addition, we as a company have a level of ambition that was recently recalculated. These are interesting conversations: how much is one minute of disruption per customer worth? This has a monetary value.

We base our level of ambition, among other things, on the target values but also on the usual service level, which you want to make a little better every year. Every year we want to resolve the disruptions a little faster. We also look at what the competitors are doing, even though it is quite similar. The ACM (Consumer and Market Authority) is the supervisor and of course it also monitors.

Appendix F Number of people experiencing electricity outage over time

Table F-I: Number of people experiencing electricity outage over time

	point in time (hours), rainfall ends at t=1							
Type of rainfall	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
18.9 mm	0	808	539	269	0	0	0	0
35.7 mm	0	1733	1733	1155	578	0	0	0
50 mm	0	1733	1733	1733	1155	578	0	0
70 mm	0	1850	1850	1850	1233	617	0	0
90 mm	0	2738	2738	2738	2738	1825	913	0

Appendix G Survey sent to the city panel [original Dutch version]

A1
Woont u in een koop- of huurwoning?
Koopwoning
Huurwoning

A2
Hoe lang verwacht u te blijven wonen in de wijk waar u nu woont?
1 jaar
2-4 jaar
5-10 jaar
langer
ik heb geen verhuisplannen

Een extreme regenbui van een paar uur kan tot gevolg hebben dat het water niet meer afgevoerd kan worden en tot overstromingen in de stad leidt. Water kan voor een aantal uren of dagen op de straat blijven staan en hierdoor schade aanrichten.

A3
Maakt u zich zorgen over de gevolgen van zo’n overstroming voor de straat waar u woont?
Ja, zeker
Een beetje
Nee

A4
Heeft u een noodvoorraad (overlevingspakket) in huis van bijvoorbeeld water, kaarsen, houdbaar eten uit blik?
Ja
Nee

Onder andere in uw wijk bestaat het risico op een onverwachtse overstroming door een extreme regenbui. We leggen u zo meteen 9 situaties voor waarin steeds enkele gevolgen van zo’n mogelijke overstroming worden beschreven. Het kan bijvoorbeeld zijn dat de elektriciteit of het mobiele netwerk plotseling uitvalt, de straten voor een langere tijd onbegaanbaar zijn, en er kunnen problemen optreden bij winkels en ziekenhuizen. Per situatie vragen we of dit risico voor u een reden zou zijn om te gaan zoeken naar een andere woonomgeving. Zo proberen we te begrijpen wat de belangrijkste voorzieningen zijn tijdens een noodsituatie.

X1A
Leest u s.v.p. onderstaande situatie over de gevolgen van een overstroming:

- Elektriciteit: de stroom valt 6 uur lang uit
- Mobiel netwerk: 12 uur lang kunt u niet bellen en internetten op uw telefoon
- Straten: 12 uur lang zijn straten onbegaanbaar met de auto en rijdt er geen OV

Als dit **1x per 2 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.
Zeker mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens → XA
Zeer mee oneens → XA

X1B (als pop-up op dezelfde page, zodat de situatie zichtbaar blijft)
Als dit **1x per 10 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.
Zeer mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens
Zeer mee oneens

X2A
Leest u s.v.p. onderstaande situatie over de gevolgen van een overstroming:

- Beschikbaarheid winkels: 1 dag zijn alle winkels gesloten
- Ziekenhuizen: 3 uur zijn alle eerste hulpposten dicht
- Elektriciteit: de stroom valt 6 uur lang uit

Als dit **1x per 2 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.
Zeer mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens → XA
Zeer mee oneens → XA

X2B (als pop-up op dezelfde page, zodat de situatie zichtbaar blijft)
Als dit **1x per 10 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.
Zeer mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens
Zeer mee oneens

X3A
Leest u s.v.p. onderstaande situatie over de gevolgen van een overstroming:

- Elektriciteit: de stroom valt 6 uur lang uit
- Mobiel netwerk: 6 uur lang kunt u niet bellen en internetten op uw telefoon
- Straten: 24 uur lang zijn straten onbegaanbaar met de auto en rijdt er geen OV

Als dit **1x per 2 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.
Zeker mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens → XA
Zeer mee oneens → XA

X3B (als pop-up op dezelfde page, zodat de situatie zichtbaar blijft)
Als dit **1x per 10 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.
Zeer mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens
Zeer mee oneens

X4A
Leest u s.v.p. onderstaande situatie over de gevolgen van een overstroming:

- Ziekenhuizen: 3 uur zijn alle eerste hulpposten dicht
- Elektriciteit: de stroom valt 6 uur lang uit
- Mobiel netwerk: 2 dagen lang kunt u niet bellen en internetten op uw telefoon

Als dit **1x per 2 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.
Zeer mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens → XA
Zeer mee oneens → XA

X4B (als pop-up op dezelfde page, zodat de situatie zichtbaar blijft)
Als dit **1x per 10 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.

Zeer mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens
Zeer mee oneens

X5A
Leest u s.v.p. onderstaande situatie over de gevolgen van een overstroming:

- Elektriciteit: de stroom valt 2 dagen uit
- Mobiel netwerk: 6 uur lang kunt u niet bellen en internetten op uw telefoon
- Straten: 12 uur lang zijn straten onbegaanbaar met de auto en rijdt er geen OV

Als dit **1x per 2 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.
Zeer mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens → XA
Zeer mee oneens → XA

X5B (als pop-up op dezelfde page, zodat de situatie zichtbaar blijft)
Als dit **1x per 10 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.
Zeer mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens
Zeer mee oneens

X6A
Leest u s.v.p. onderstaande situatie over de gevolgen van een overstroming:

- Beschikbaarheid winkels: 1 dag is alles gesloten behalve een enkele supermarkt
- Ziekenhuizen: 12 uur zijn alle eerste hulpposten dicht
- Elektriciteit: de stroom valt 12 uur lang uit

Als dit **1x per 2 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.
Zeer mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens → XA
Zeer mee oneens → XA

X6B (als pop-up op dezelfde page, zodat de situatie zichtbaar blijft)
Als dit **1x per 10 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.
Zeer mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens
Zeer mee oneens

X7A
Leest u s.v.p. onderstaande situatie over de gevolgen van een overstroming:

- Ziekenhuizen: 3 uur zijn alle eerste hulpposten dicht
- Elektriciteit: de stroom valt 2 dagen uit
- Mobiel netwerk: 6 uur lang kunt u niet bellen en internetten op uw telefoon

Als dit **1x per 2 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.
Zeer mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens → XA

Zeer mee oneens → XA

X7B (als pop-up op dezelfde page, zodat de situatie zichtbaar blijft)
Als dit **1x per 10 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.
Zeer mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens
Zeer mee oneens

X8A
Leest u s.v.p. onderstaande situatie over de gevolgen van een overstroming:

- Ziekenhuizen: 24 uur zijn alle eerste hulpposten dicht
- Elektriciteit: de stroom valt 6 uur lang uit
- Mobiel netwerk: 12 uur lang kunt u niet bellen en internetten op uw telefoon

Als dit **1x per 2 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.
Zeer mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens → XA
Zeer mee oneens → XA

X8B (als pop-up op dezelfde page, zodat de situatie zichtbaar blijft)
Als dit **1x per 10 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.
Zeer mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens
Zeer mee oneens

X9A
Leest u s.v.p. onderstaande situatie over de gevolgen van een overstroming:

- Beschikbaarheid winkels: 1 dag is alles gesloten behalve een enkele supermarkt
- Ziekenhuizen: 3 uur zijn alle eerste hulpposten dicht
- Elektriciteit: de stroom valt 2 dagen uit

Als dit **1x per 2 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.
Zeer mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens → Z99
Zeer mee oneens → Z99

X9B (als pop-up op dezelfde page, zodat de situatie zichtbaar blijft)
Als dit **1x per 10 jaar voorkomt**, is dit voor mij een reden om naar een andere woonomgeving te gaan zoeken.
Zeer mee eens
Mee eens
Niet mee eens, niet mee oneens
Mee oneens
Zeer mee oneens

Z99
Wilt u nog iets toelichten aan de gemeente over dit onderwerp?
____
[Verstuur]
Bedankt voor het invullen van deze vragenlijst.

Appendix H Translation of example questions in the survey, sent to the city panel

A1
Do you live in a house for sale or rent?
For sale
Rental house

A2
How long do you expect to continue living in the area where you now live?
1 year
2-4 years
5-10 years
longer
I don't have relocation plans

An extreme rainstorm of a few hours can result in the water not being able to be drained anymore and leading to floods in the city. Water can remain on the street for several hours or days, causing damage.

A3
Are you worried about the consequences of such a flood for the street where you live?
Yes, for sure
A little
No.

A 4
Do you have an emergency supply (survival kit) in the house of, for example, water, candles, canned food?
Yes
No.

In your neighbourhood there is a risk of unexpected flooding due to an extreme rain shower. We will shortly present to you 9 situations in which some of the consequences of such a possible flood are described. For example, the electricity or mobile network may suddenly fail, the streets may be impassable for an extended period of time, and problems may arise at shops and hospitals. For each situation we ask whether this risk would be a reason for you to look for a different living environment.
In this way we try to understand what the most important facilities are during an emergency situation.

X1 A
Please read the situation below about the consequences of a flood :

- Electricity: no electricity for 6 hours
- Mobile network: You can not make calls and use internet on your phone for 12 hours
- Streets: For 12 hours the streets are impassable by car and there is no public transport

If this **happens once every 2 years** , this is a **reason** for me to start looking for a different living environment.
Strongly agree
Agree
Neither agree nor disagree
Disagree
Strongly disagree

X1 B (as a pop-up on the same page, so that the situation remains visible)
If this **happens once every 10 years** , this is a **reason** for me to start looking for a different living environment.
Strongly agree
Agree
Neither agree nor disagree
Disagree → Z99
Strongly disagree → Z99

X2A
Please read the situation below about the consequences of a flood:

- Availability of shops: All shops are closed for 1 day
- Hospitals: All first aid stations are closed for 3 hours
- Electricity: the power is off for 6 hours

If this **happens 1x every 2 years** , this is a **reason** for me to start looking for a different living environment.
Strongly agree
Agree
Neither agree nor disagree
Disagree
Strongly disagree

X2B (as a pop-up on the same page, so that the situation remains visible)
If this **happens once every 10 years, it's a reason** for me to start looking for a different living environment.
Strongly agree
Agree
Neither agree nor disagree
Disagree → Z99
Strongly disagree → Z99

[Survey continuous with in total nine questions consisting of an A and B part]

Z99

Would you like to explain something to the municipality about this subject?

____

[Send]

Thank you for completing this questionnaire.

Appendix I Predicted probabilities of figure 49 and figure 50

Table I-I: predicted probabilities of figure 49

10 year event	3h	6h	9h	12h	15h	18h	21h	24h	27h	30h	33h	36h	39h	42h	45h h	48
Electricity network		4.07%	4.23%	4.40%	4.57%	4.75%	4.94%	5.14%	5.34%	5.55%	5.76%	5.99%	6.22%	6.46%	6.71%	6.97%
Hospital network	3.84%	3.93%	4.01%	4.10%	4.18%	4.27%	4.37%	4.46%								
Mobile network		3.83%	3.87%	3.91%	3.95%	3.98%	4.02%	4.06%	4.10%	4.14%	4.18%	4.21%	4.25%	4.30%	4.34%	4.38%

Table I-I: Predicted probabilities of figure 50.

2 year event	3h	6h	9h	12h	15h	18h	21h	24h	27h	30h	33h	36h	39h	42h	45h	48h
Electricity network		12.06%	12.50%	12.95%	13.42%	13.90%	14.39%	14.90%	15.43%	15.96%	16.52%	17.09%	17.67%	18.27%	18.88%	19.51%
Hospital network	11.45%	11.68%	11.91%	12.14%	12.38%	12.62%	12.87%	13.12%								
Mobile network		11.43%	11.53%	11.63%	11.73%	11.83%	11.93%	12.04%	12.14%	12.25%	12.35%	12.46%	12.57%	12.68%	12.79%	12.90%

Appendix J Parameter estimates and model fitting parameters of the robustness check models

The continuous model of the ordinal regression was run again with two alterations in the dataset to check for robustness. The first alteration was to leave out the surveys of panellists who replied the same answer to all the questions (second column 'dataset with variation in dependent variable'). In general the influence of the infrastructure variables increased, but the order remained the same (*electricity* having the highest influence, *mobile network* the lowest). The parameters for the socio-demographic variables did not change much. Only the difference between education categories *lower* and *middle* became smaller.

The second variation in dataset was to only look at the answers of the first question with a recurrence time of two years (first column 'dataset recurrence time = 2 years'). The parameters changed as expected: infrastructure variables increased in influence and remained significant. Some socio-demographic variables turned out insignificant, for example differences between middle and high education, and between house owners and tenants. The differences between age categories turned out to be significant for all categories in this model, and a stronger influence of the age category 16-29 having even lower tolerance levels.

Table J-I: Parameter estimates of the robustness check models.

	Dataset recurrence time = 2 years		Dataset with variation in dependent variable	
Thresholds dependent variable	Parameter estimate	Significance	Parameter estimate	Significance
Likert answer Strongly agree + agree	-2.298	0.000	-3.001	0.000
Likert answer Strongly disagree + disagree	-1.235	0.000	-1.850	0.000
Infrastructure variables				
Electricity continuous	-0.015	0.000	-0.017	0.000
Mobile network continuous	-0.005	0.001	-0.005	0.000
Street continuous	-0.007	0.204	-0.009	0.050
Hospital continuous	-0.009	0.006	-0.008	0.004
Shops X1	-0.024	0.678	-0.145	0.003
Shops X2	0.005	0.931	0.030	0.532
Recurrence time reference: 10 years				
2 years			-1.434	0.000
Situation set reference: set 3				
Situation set 1	0.057	0.608	0.103	0.267
Situation set 2	0.015	0.827	-0.025	0.659
Socio-demographic variables				
Gender reference: Male				
Female	0.082	0.085	0.153	0.000
Household reference: two persons				
Other	0.352	0.001	0.130	0.174
Single person	0.011	0.842	-0.070	0.155
Family	-0.234	0.001	-0.055	0.345
Education reference: high				
Middle	-0.058	0.376	-0.258	0.000
Low	-0.519	0.000	-0.246	0.019
Age reference: 60-69 years				
16-29 years	-0.550	0.000	-0.349	0.001
30-39 years	-0.208	0.018	-0.090	0.212
40-49 years	-0.191	0.012	-0.103	0.110
50-59 years	-0.260	0.000	-0.220	0.000

70+	0.226	0.004	0.255	0.000
District reference: Centrum				
Segbroek	0.130	0.014	0.166	0.000
Scheveningen	-0.057	0.440	0.323	0.000
Reference: house owner				
Tenant	0.119	0.056	0.168	0.001
Expected stay reference: 11 years or longer				
5-10 years	-0.368	0.000	-0.142	0.006
2-4 years	-0.382	0.000	-0.281	0.000
1 year	-0.700	0.000	-0.429	0.000
Worry about flooding: no				
A little	-0.967	0.000	-0.632	0.000
Yes	-0.969	0.000	-0.832	0.000

TableJ-II: Model fitting parameters of the robustness check models.

	recurrence time 2 years dataset		Variation dataset	
	Chi-Square	Significance	Chi-Square	Significance
Model fitting information				
Intercept vs prediction	810.102	0.000	1986.801	0.000
Goodness-of-fit				
Pearson	12395.188	0.098	19318.408	0.085
Deviance	12387.221	0.107	17859.105	1.000
ρ-Square				
Nagelkerke		0.126		0.199
Cox and Snell		0.110		0.173
McFadden		0.056		0.094

Appendix K Used non-acceptance rates for all scenarios

Table K-I: Used non-acceptance rates for all scenarios.

	0	1	2	3	4	5	6	7	8	9	10	11	12
Electricity RT **10** year	0.00%	0.73%	1.46%	2.19%	2.92%	3.65%	4.39%	4.47%	4.55%	4.64%	4.72%	4.80%	4.885%
Electricity RT 10 year indiff. Cumm	0.00%	2.00%	3.99%	5.99%	7.98%	9.98%	11.97%	12.18%	12.39%	12.59%	12.80%	13.01%	13.22%
Electricity RT **2** year	0.00%	2.16%	4.31%	6.47%	8.62%	10.78%	12.93%	13.15%	13.37%	13.60%	13.82%	14.04%	14.26%
Electricity RT 2 year indiff. Cumm.	0.00%	5.10%	10.19%	15.29%	20.38%	25.48%	30.58%	30.98%	31.39%	31.80%	32.21%	32.62%	33.03%
Scenario: RT 1 year	0.00%	2.45%	4.89%	7.34%	9.78%	12.23%	14.68%	14.92%	15.17%	15.41%	15.66%	15.90%	16.15%
Scenario: RT 5 year	0.00%	1.45%	2.91%	4.36%	5.82%	7.27%	8.73%	8.88%	9.04%	9.20%	9.35%	9.51%	9.67%
Scenario: RT 25 year	0.00%	0.08%	0.17%	0.25%	0.34%	0.42%	0.50%	0.51%	0.52%	0.53%	0.54%	0.55%	0.56%
Scenario: RT 50 year	0.00%	0.00%	0.00%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%
Scenario young people	0.00%	1.00%	2.00%	2.99%	3.99%	4.99%	5.99%	6.10%	6.21%	6.32%	6.43%	6.54%	6.65%
Scenario low education	0.00%	1.30%	2.59%	3.89%	5.19%	6.49%	7.78%	7.93%	8.07%	8.21%	8.35%	8.49%	8.64%
Streets RT 10 year	0.00%	0.82%	1.64%	2.46%	3.28%	4.11%	4.93%	5.10%	5.27%	5.44%	5.61%	5.78%	5.95%
Street RT 10 year indiff. Cumm.	0.00%	2.22%	4.44%	6.66%	8.88%	11.10%	13.32%	13.73%	14.15%	14.56%	14.97%	15.39%	15.80%
Streets 2 year	0.00%	2.39%	4.79%	7.18%	9.58%	11.97%	14.37%	14.81%	15.25%	15.69%	16.13%	16.57%	17.01%
Streets 2 year indiff. Cumm	0.00%	5.54%	11.08%	16.61%	22.15%	27.69%	33.23%	33.99%	34.75%	35.51%	36.28%	37.04%	37.80%
Scenario: RT 1 year	0.00%	2.71%	5.42%	8.14%	10.85%	13.56%	16.27%	16.76%	17.24%	17.73%	18.21%	18.70%	19.18%
Scenario: RT 5 year	0.00%	1.62%	3.25%	4.87%	6.50%	8.12%	9.75%	10.07%	10.38%	10.70%	11.02%	11.34%	11.65%
Scenario: RT 25 year	0.00%	0.09%	0.19%	0.28%	0.38%	0.47%	0.57%	0.59%	0.61%	0.63%	0.65%	0.67%	0.69%
Scenario: RT 50 year	0.00%	0.00%	0.00%	0.01%	0.01%	0.01%	0.01%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%
scenario young people	0.00%	1.12%	2.24%	3.36%	4.47%	5.59%	6.71%	6.94%	7.17%	7.39%	7.62%	7.85%	8.08%
scenario low education	0.00%	1.45%	2.90%	4.35%	5.80%	7.26%	8.71%	8.99%	9.28%	9.57%	9.86%	10.15%	10.43%

Yellow values are known. Blue values are estimated effects. White values are interpolated. Due to rounding off the parameters, slight differences can be observed between the stated values in chapter 5.

Appendix L Input parameters to establish tolerance levels of all scenarios

Table L-I: Input parameters to establish tolerance levels of all scenarios.

Variables	Parameters/effects
Threshold disagree	-2.850
Threshold indifferent	-1.763
Electricity 6 hours	0.232
Electricity 12 hours	0.119
Streets 6 hours	0.11
Streets 12 hours	-0.09
Recurrence time 1 year	-1.32188*
Recurrence time 2 year	-1.175
Recurrence time 5 year	-0.73438*
Recurrence time 10 year	0
Recurrence time 25 year	2.203125*
Recurrence time 50 year	5.875*
Scenario young people in area	-0.328
Scenario lower educated people	-0.61

* These parameters are estimates based on inter/extrapolation of the other values of the recurrence time parameters.

Appendix M People not accepting disruption over time, climate change scenarios

Table M-I: People not accepting disruption to the electricity network, climate change scenarios.

People not accepting electricity disruption																
Event - Time (hours)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**Maximum values**
18.9mm, RT 2 years	0	17	23	17	0	0	0	0	0	0	0	0	0	0	0	23
18.9mm, RT 1 year (climate change)	0	20	26	20	0	0	0	0	0	0	0	0	0	0	0	26
35.7mm, RT 10 years	0	13	25	25	17	0	0	0	0	0	0	0	0	0	0	25
35.7mm, RT 5 years (climate change)	0	25	50	50	34	0	0	0	0	0	0	0	0	0	0	50
50mm, RT 50 years	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50mm, RT 25 years (climate change)	0	1	3	4	4	2	0	0	0	0	0	0	0	0	0	4

Table M-II: People not accepting disruption tot he road network, climate change scenarios.

People not accepting road network disruption																
Event - Time (hours)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**Maximum value**
18.9 mm RT 2 years	0	439	585	439	0	0	0	0	0	0	0	0	0	0	0	585
18.9mm RT 1 years (climate change)	0	497	663	497	0	0	0	0	0	0	0	0	0	0	0	663
35.7 mm RT 10 years	0	339	626	859	1040	1168	1243	1122	773	399	0	0	0	0	0	1243
35.7mm RT 5 years (climate change)	0	671	1238	1700	2058	2311	2459	2215	1524	785	0	0	0	0	0	2459
50mm RT 50 years	0	1	2	3	4	5	6	6	5	5	5	3	2	0	0	6
50mm RT 25 years (climate change)	0	51	96	137	172	202	227	219	210	201	189	130	67	0	0	227

Appendix N People not accepting disruption over time, different socio-demographic scenarios

Table N-I: People not accepting disruption to the electricity network, socio-demographic scenarios.

Electricity disruption scenarios																
Event - Time (hours)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**Maximum value**
Base scenario	0	13	25	25	17	0	0	0	0	0	0	0	0	0	0	25
Young scenario	0	17	35	35	23	0	0	0	0	0	0	0	0	0	0	35
Low education scenario	0	22	45	45	30	0	0	0	0	0	0	0	0	0	0	45

Table N-II: People not accepting disruption to the road network, socio-demographic scenarios.

Road network disruption scenarios																
Event - Time (hours)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**Maximum value**
Base scenario	0	339	626	859	1040	1168	1243	1122	773	399	0	0	0	0	0	1243
Young scenario	0	462	852	1171	1417	1591	1693	1527	1051	542	0	0	0	0	0	1693
Low education scenario	0	600	1106	1519	1838	2064	2197	1980	1362	702	0	0	0	0	0	2197