Hidden danger

Mapping consequences of underground water infrastructure failure to guide asset management

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TU Delft

Deltares
Enabling Delta Life

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by

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Preface

Growing up in Limburg, my passion for cycling the hills and the interest in (the absence of) water developed. Heavy precipitation events frequently occurred, causing a flow along the hills and flooding of the lower parts of the streets. I was wondering where the water came from and where it would end up. I think that is where the curiosity for water management started and what inspired me to start my studies in Civil Engineering. I am glad that I have been given the opportunity to continue my masters in water management and to work on this topic, contributing to the knowledge of urban water management, keeping the urban areas liveable.

This thesis concludes my master's degree in Water Management at the Delft University of Technology. I can say it has been quite a mountain to climb. Starting in the mountain valley, this research enabled me to study a part of water management I had not yet explored; the underground water infrastructure.

I would like to thank my graduation committee members, who guided me and motivated me to keep on climbing. Firstly, I would like to acknowledge the insights and the advice provided by my daily supervisor. Thank you Didrik, for your encouragement to let me being part of your research. Jeroen, for your constructive feedback and the freedom to explore this road in my way. It gave me new insights, being part of the demurrage. Finally, I would like to thank Hessel for helping me to set up this project and for your independent view on my research. I also want to acknowledge the support of the people at the municipality of Utrecht and Vitens. Special thanks to Javier, Rutger and Bart. Moreover, in general, I would like to thank the colleagues of Deltares.

Lastly, I would like to give special thanks to my friends and family. I would like to thank you for your support along the road. You really motivated me to reach the top and look around.

It has been a fantastic adventure, finishing on top of the mountain. At this point, there is an amazing view over the valley, seeing all the mountains I have climbed to obtain the MSc degree in Civil Engineering.

Charlotte Mekel
Delft, August 2020

Summary

Continuous functioning of sewer systems and water distribution networks is crucial for liveability, public health and economic prosperity in urban areas. Progressive deterioration of these underground water infrastructures leads to an increased probability of failure. Maintenance is needed to ensure a desired level of functioning. For municipalities and drinking water companies as asset owners, the trend is to develop risk-based asset management. A risk-based asset management strategy links the likelihood of failure with the consequences. Hence, knowledge is needed on the condition of the underground water infrastructure and the consequences in case of failure. Within this strategy, a risk assessment should be performed to prioritise the maintenance and renewal of underground water infrastructure. Based on their criticality, resources can be applied appropriately. The more critical a conduit segment, the more important it is to perform maintenance.

To contribute to risk-based asset management, this study investigates the consequences of failure in sewer systems and water distribution networks. In this research, a methodology is developed for mapping consequences of underground water infrastructure failure to guide asset management. Including the consequences of underground water infrastructure failure in the risk determination may lead to a different prioritisation of maintenance activities. Three failure mechanisms are considered: structural sewer failure, hydraulic sewer failure and water distribution network failure. Structural sewer failure leads to partial or complete loss of the load-carrying capacity, whereas hydraulic sewer failure occurs when a system does not meet serviceability requirements for system performance. For water distribution networks, it is assumed that hydraulic failure (caused by overpressure) and structural failure occur simultaneously. Hence, no distinction is made between failure mechanisms in water distribution networks.

Using a screening method, the consequences of underground water infrastructure failure are mapped. The consequences of failure are expressed as the affected area and the characteristics of the built environment. The affected area consists of the sinkhole area and the flood zone. The characteristics of the built environment are displayed by means of consequence categories. Within this study, five different consequence categories are taken into account, using hydraulic modelling and (open) classified data. The consequence categories are: 1) Damage to buildings 2) Traffic obstruction 3) Impact on human health 4) Costs of conduit reconstruction 5) Drinking water supply outage. A flat, typical Dutch study area in Tuindorp (Utrecht) is used to test the methodology. For these five consequence categories, findings are illustrated and compared with the results of the hydraulic network functioning according to the Graph Theory method (GTM). This GTM determines the effects of failure of individual conduits on the functioning of a system as a whole, based on a simplified network structure using links and nodes.

Results of the analyses show a positive relation between the individual consequences in case of hydraulic sewer failure. For example, critical conduits in the category 'damage to buildings', are critical for 'impact on human health' as well. Besides, there is a positive relation between the consequence categories and the hydraulic network functioning. Conduits with large diameters are stated as critical for both methods, yet dead-end segments are only critical for hydraulic network functioning. Contradictory, individual consequences are uncorrelated for structural sewer failure and water distribution network failure. The consequences are independent and can not be linked. Besides, there is no relation between the hydraulic network functioning and the individual consequences of structural sewer failure and water distribution network failure.

This research shows that including the consequences of failure in the risk determination inevitably leads to a different order of conduit criticality, when compared to the criticality according to the hydraulic network functioning. The results of the research show that individual consequences are independent; it depends on the failure mechanism and consequence category, whether a conduit segment is critical or not. To provide risk-based asset management, it is needed to include all individual consequence categories and all failure mechanisms. It is recommended to study the probability of failure, as well as the importance of individual consequences to complete risk-based asset management and improve the applicability.

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Introduction

In this chapter, the subject of this thesis is introduced. A concise description of the current issues in the maintenance and rehabilitation of underground water infrastructure is provided, which addresses the relevance of this research. Research questions define the objective of the study. Besides, a scope is set.

1.1. Research context

Underground water infrastructure has evolved throughout history, and today it is a vital component of a sustainable urban system (Burian and Edwards, 2002). Continuous functioning of this infrastructure is crucial for liveability, public health and economic prosperity in the urban areas (Piratla et al., 2015). Progressive deterioration of this infrastructure leads to an increased probability of failure. The underground water infrastructure includes sewer systems and water distribution networks. In the Netherlands, 80% of the yearly 6,000 to 7,000 water distribution network failures contain conduits with a small diameter (<150mm) and have few consequences (Elshof, 2015). However, some of the main breaks result in significant economic, environmental and societal consequences. An example of a catastrophic conduit failure is the flooding of the VU Medical Centre in Amsterdam. In September 2015, a conduit of the water distribution network broke down in front of the hospital, with flooding as a result. Total damage: 15 million litre water, evacuation of over 300 patients and (insured) costs of €34,800,000 (NIBHV, 2016). Another example is the 250-metre long fatberg in the sewer system of the Whitechapel neighbourhood, London (Engelhaupt, 2017). This blockage weighed 130 tonnes and was the size of 11 double-decker buses (Engelhaupt, 2017). If the blockage had not been discovered in time, failure could have occurred with severe adverse consequences and serious environmental problems (Anbari et al., 2017).

Relevance of the research

After realisation, sewer systems and drinking water networks need to be maintained continuously to ensure a desired level of functioning. The task of municipalities and drinking water companies as asset owners is to maintain a minimal level of service at a reasonable cost while meeting environmental requirements (Aberkrom et al., 2016, Vitens, 2018). Maintenance requires both effort and financial investments. Since these resources are limited, maintenance strategies are applied.

For water distribution networks, often reactive maintenance strategies are applied. The reactive strategy is characterised by action undertaken after the appearance of failure. For sewer systems, reactive maintenance strategies were applied up until the 1970s, as the focus was on design and construction of underground water infrastructure (Post, 2016). The increasing number of failures pushed organisations to shift towards a more proactive strategy in the 1980s (Post, 2016). The proactive strategy is characterised by activities, such as inspections, undertaken before failure occurs.

For both asset owners, the trend is to develop risk-based asset management. Within a risk-based asset management strategy, a risk assessment should be performed such that it reflects the organisations' perception of risk (Salman and Salem, 2012). Risk is defined as the likelihood of an undesired event multiplied by the consequences (Jonkman et al., 2018, Kaplan and Garrick, 1981, Vlek, 1996). Failure probability depends on multiple factors, including material type and location of the conduits. The consequences of failure are determined by the combination of the affected area and characteristics of the built environment. Flooding of buildings, environmental issues and accidents are examples of consequences of failure.

When the probability of failure and the consequences are known, the risk assessment can be completed and prioritisation of maintenance activities can be done. A flow chart can be used to illustrate the appropriate strategy that is to be applied, see Figure 1.1. When either the consequences or probability of conduit failure is minimal, organisations' strategy can be reactive. A proactive strategy is required when the consequences and probability of failure are substantial.

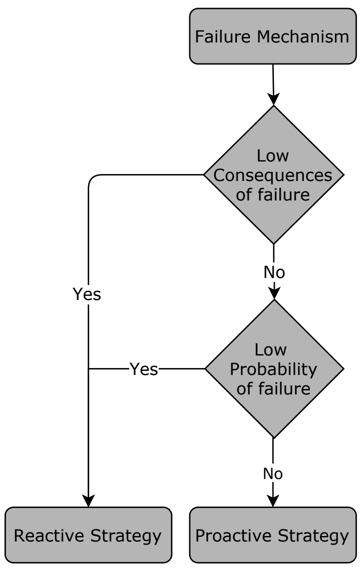


Figure 1.1: Flowchart for the asset management strategy of underground water infrastructure

1.2. Problem statement

Underground water infrastructure needs to be maintained in order to provide continuous functioning. Strategies are required to prioritise maintenance and rehabilitation of the sewer systems and water distribution networks. For municipalities and drinking water companies as asset owners, the trend is to develop risk-based asset management. A risk-based asset management strategy links the probability of failure with the consequences in order to be able to apply resources properly. However, there is a lack of knowledge on the condition of the underground water infrastructure and consequences in case of failure, leading to an incomplete risk determination. This may result in the inappropriate application of resources. Besides being expensive, citizens may be exposed to the consequences of a failure such as water damage and accidents. It is therefore required for the asset owners to invest in the completion of the risk determination in order to apply a risk-based asset management strategy (Aberkrom et al., 2016).

1.3. Research objective

In order to contribute to risk-based asset management, this research focuses on mapping the consequences of underground water infrastructure failure. Including the consequences of underground water infrastructure failure in the risk determination may lead to a different prioritisation of maintenance activities. With the use of hydraulic modelling and (open) classified data, consequences of failure in the built environment are mapped. Results show the criticality of the individual elements. These results are compared with the criticality of elements according to a reference method. In this study, the reference conduit criticality is determined by the hydraulic functioning of the network according to the Graph Theory method (GTM), see Section 3.1. The main research objective is defined as follows:

Development of a methodology for mapping consequences of underground water infrastructure failure to guide asset management.

Research questions are formulated in order to meet the aim of the study.

1. What are possible consequences of hydraulic and structural failure of underground water infrastructure?
2. How can the consequences of failure be assessed, using hydraulic modelling and (open) classified data?
3. What is the effect of the individual consequences of failure on the conduit criticality in underground water infrastructure?

1.4. Research scope

This research focuses on consequences of underground water infrastructure failure. The study outcomes are valid for urbanised areas with managed sewer systems and water distribution networks, mainly in The Netherlands. The following aspects demarcate the scope:

1. This research focuses on the 'underground water infrastructure', which are the 'sewer systems' and 'water distribution networks'. Only main conduits are taken into account, leaving connections to households aside.
2. Regarding sewer systems, both structural and hydraulic failure mechanisms are taken into account. Structural sewer failure of a system can be described as partial or complete loss of the load-carrying capacity. Hydraulic sewer failure represents the internal failure due to for example, fully blockage of the system.
3. This research focuses on the consequences that can be investigated using hydraulic modelling and (open) classified data.

1.5. Report outline

A visualisation of the research set up is presented in Figure 1.2. Following this introduction, the report continues with a theoretical background, which focuses on the description of underground water infrastructure, the risk assessment and existing determination of consequences. Subsequently, Chapter 3 introduces the study area and describes the methodology, divided into the affected area caused by failure and the consequences of failure. The methods are followed by the results in Chapter 4. In Chapter 5 the methodology and results are discussed. Finally, conclusions are drawn, and recommendations are presented in Chapter 6. This final chapter provides answers to the research questions posed in Section 1.3.

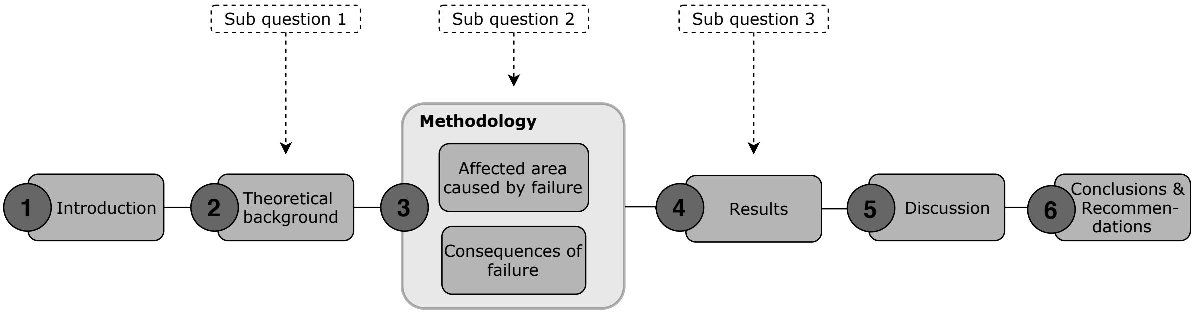
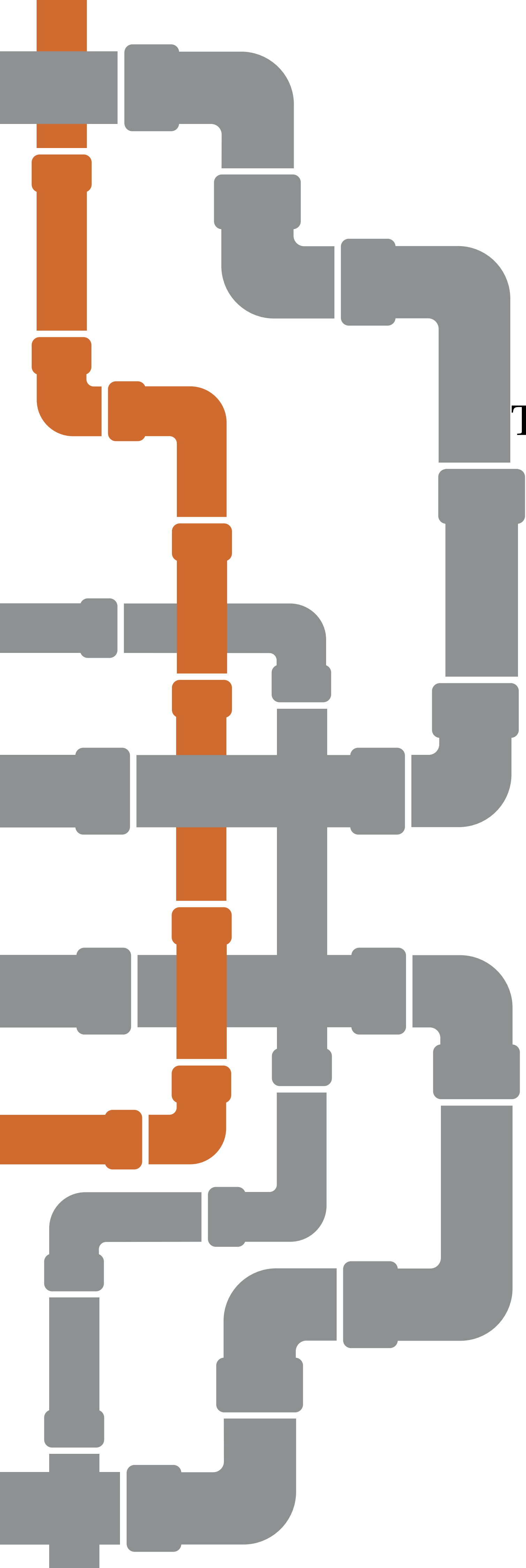


Figure 1.2: Visualisation of the report structure



2

Theoretical background

In this chapter, a theoretical background from literature is provided. The history and current state of the underground water infrastructure is described and failure mechanisms are discussed. Subsequently, the probability of failure and possible consequences of failure are discussed answering the first research question: ‘What are possible consequences of hydraulic and structural failure of underground water infrastructure?’ A conclusion is drawn about the consequences taken into account in this research. Finally, existing methods to determine the consequences of failure are presented.

2.1. History of underground water infrastructure

Humans were living a nomadic life, being constantly on the move, until the first permanent settlements almost 10,000 years ago (GreenBlue Urban, 2017). Once settled, humans started an agrarian way of life which led to rapid population growth. This new way of living resulted in the construction of ancient villages that were highly dependent on water (Vuorinen et al., 2007). Additionally, contaminated water induced severe health risks. Therefore, pure water, such as springs and wells, became a prerequisite for a successful civilisation (Vuorinen et al., 2007). Several ancient civilisations have built advanced urban infrastructures, such as roads, water distribution networks and sewer systems (Burian and Edwards, 2002). Examples of early sewer systems are found by the Indus civilisation of around 2550 B.C. and the Aegean civilisation of 3400-1200 B.C. (Gray, 1940). The ancient terra-cotta pipes that were used, still sound these days after nearly 5000 years (Gray, 1940).

Until the age of enlightenment rivers contained relatively clean water that supplied civilisations (GreenBlue Urban, 2017). However, drainage and sewage disposal became a significant problem in the 19th century. This led to the outbreak of cholera epidemics in cities around the world. John Snow (1813–1858) demonstrated epidemiologically that it was a waterborne disease, caused by the contraction of contaminated drinking water (GreenBlue Urban, 2017, Vinten-Johansen et al., 2003). It was at this point that organisations started to improve sanitary in urban environments. At the end of the 19th century, culverted sewer systems were developed to drain the urban waste and stormwater (GreenBlue Urban, 2017). This resulted in cleaner drinking water wells and additionally resolved urban odour problems.

In The Netherlands, the first household drinking water connection dated from the 1850s, see Figure 2.1 (Langeveld, 2004). Due to the development of water distribution networks, an increased amount of wastewater needed to be transported. Though, it took until 1900 for sewer systems to be connected to transport wastewater. The hygienic transition to sewer systems in The Netherlands is characterised as slow and relatively late compared to other international cities (Geels, 2006). By way of comparison, the transition in Hamburg and Amsterdam started in 1843 and 1913, respectively (Geels, 2006). Since the 1970s almost 100% of the households in The Netherlands are connected to the drinking water network.

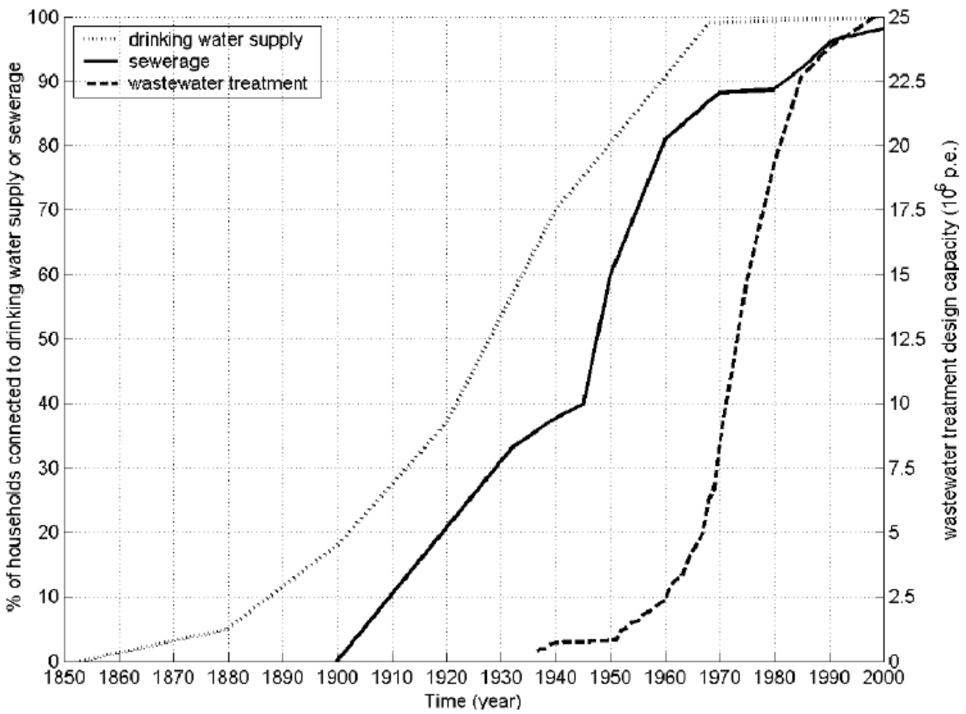


Figure 2.1: Development of the sanitary infrastructure in the Netherlands (Langeveld, 2004)

2.2. Underground water infrastructure

Following Section 2.1, this section continues with a description of the current underground water infrastructure in The Netherlands. Main characteristics of sewer systems and water distribution networks are discussed. The relation between these infrastructures is shown in Figure 2.2. Subsection 2.2.3 explains the differences between the underground water infrastructures.

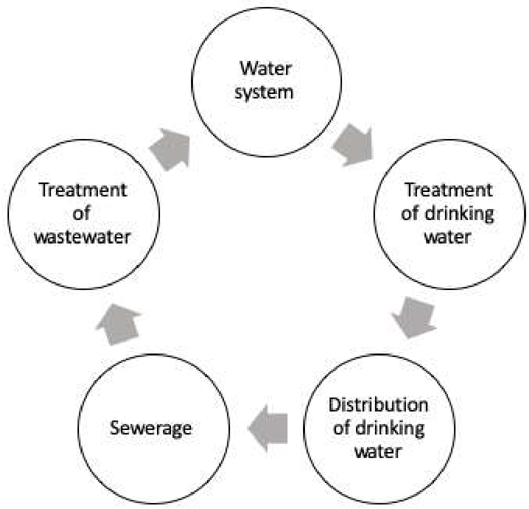


Figure 2.2: Water cycle, adapted from Vewin (2018)

2.2.1. Sewer system

A sewer system transports sewage (and stormwater) from households, commercial areas and industry to a wastewater treatment plant (WWTP). Most often, sewage is treated to control water pollution before entering the streams again. Some main components of a sewer system are conduits, manholes, pumps and the WWTP, see Figure 2.3. In 1993, the Dutch 'Environmental Management Act' (Wet Milieubeheer) was introduced, obligating municipalities to make a strategic sewer plan, including policy and resources to maintain the systems (Rijkswaterstaat, 2019). Tasks are, among others, planning, maintenance and research (Stichting Rioned, 2017). New methods were developed to maintain sewer systems, such as the closed-circuit television video (CCTV), where a small camera enters the sewers to determine the current state. Furthermore, cleaning protocols, budget allocation and renewal strategies were formulated, being the basis of today's asset management (Post, 2016). To fulfil the municipal water tasks, municipalities provide new sewer plans around every four years (Rijkswaterstaat, nd). Costs of these plans are covered by issuing taxes to households and companies in the corresponding municipality. In 2020, the average expenses per household are €199, ranging from a minimum of €78 and a maximum of €534 (COELO, 2020).

Several materials can be used for the construction of sewers. In The Netherlands, 72% of the systems consist of concrete pipes, where both round and oval pipes are applied (Stichting Rioned, 2010). Plastic conduits, mainly PVC, are used in 25% of the networks. These conduits are placed in areas with clay or peat soils, as this material is lighter than concrete and therefore reduces the possibility of soil (and conduit) subsidence (Stichting Rioned, 2010). The final 3% consists of ceramics or other materials (Stichting Rioned, 2010).

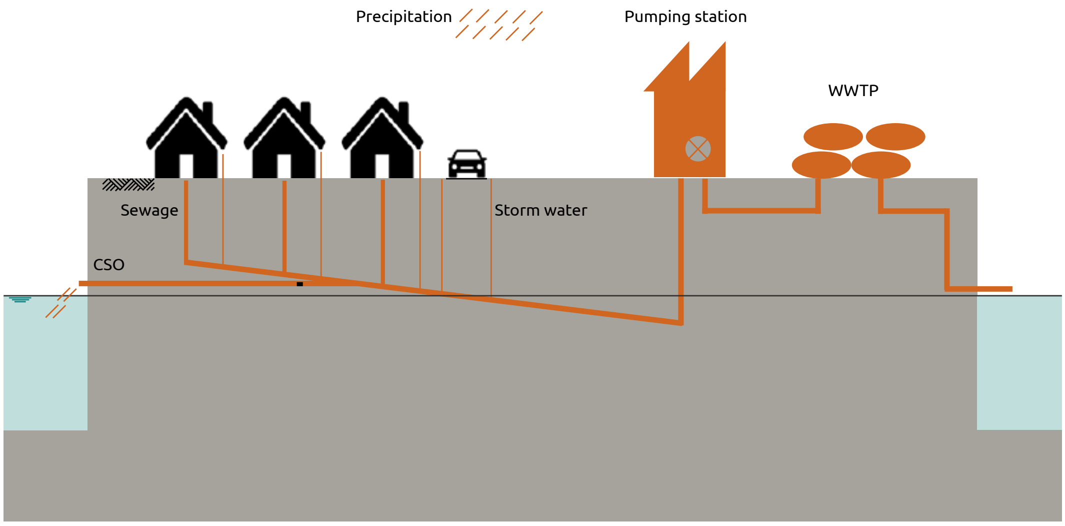


Figure 2.3: Visualisation of a combined sewer system

Network types

In The Netherlands, three main types of sewer systems can be distinguished: combined, separate and 'improved' separate sewer systems (Stichting Rioned, 2017). In The Netherlands, 75% of the systems are combined, where both wastewater and stormwater are collected. In the case of an extreme rainfall event, a combined sewer overflow (CSO) takes place. Here, the amount of water that can not be transported to the WWTP is released and flows untreated into the local waterways. This can cause serious pollution to the environment. Secondly, separate sewer systems transport wastewater to the WWTP and stormwater directly to the local streams. The WWTP receives less water to be treated compared to the combined system, and no CSO can take place. However, wrong connections lead to untreated sewage into streams. In other words, urban waste flows into the stormwater system and is left untreated when discharged. 18% of the systems are separate types. Finally, the 'improved' separate sewer system also consists of a separate wastewater and stormwater system and is applied in 7% of the networks. Here, systems are connected such that part of the stormwater ('first flush') flows to the WWTP as well as the wastewater that ended up in the stormwater system.

2.2.2. Water distribution network

The water distribution network is part of the water supply system that includes carrying potable water from a centralised treatment plant to consumers, satisfying the water requirements of households, commerce, industry and fire brigades (King Fahd University of Petroleum and Minerals, nd, National Research Council, 2006). Network requirements are to deliver an appropriate quantity, quality and pressure to costumers. Moreover, the 'Drinking Water Act' (Drinkwaterwet) requires drinking water companies to supply reliable drinking water in order to protect the public health against risks in supply or provision of tap water (Drinkwaterwet, 2015, Waterleidingwet, 2009). The water supply network consists of, among others, conduits, pumps, valves, storage tanks, reservoirs, meters and fittings (National Research Council, 2006). A visualisation of a water supply system is provided in Figure 2.4. Generally, the conduit segments of the water distribution network are located below sidewalks, following the layouts of roads. According to Adeosun (2014), four main types of water distribution networks are applied: Grid, Ring, Radial and Dead End system. The minimum required pressure in the conduits is 150kPa at all times at the point of delivery (Vewin, 2018). On average, the water pressure is higher to achieve this requirement across the entire network (Vewin, 2018). Conduits mainly consist of PVC or AC and to a lesser extent of PE and cast iron (Vewin, 2018).

In The Netherlands, ten companies produce and distribute drinking water (Vewin, 2018). These companies are responsible for the maintenance and renewal of the drinking water network. The water is mainly abstracted from surface waters or groundwater and treated in a drinking water treatment (DWTP). The 'Environmental Management Act' obligates drinking water companies to protect their groundwater (Rijkswaterstaat, 2019). Furthermore, the 'Dutch Drinking Water Decree' specifies the maximum levels of substances and microorganisms that drinking water may contain (Vewin, 2018). As a result, the water in The Netherlands is of potable and constant quality. The average domestic use of drinking water is 120l per person per day, with prices ranging from €0.63 to €1.32 per cubic metre in 2019 (Vastelastenbond, 2018).

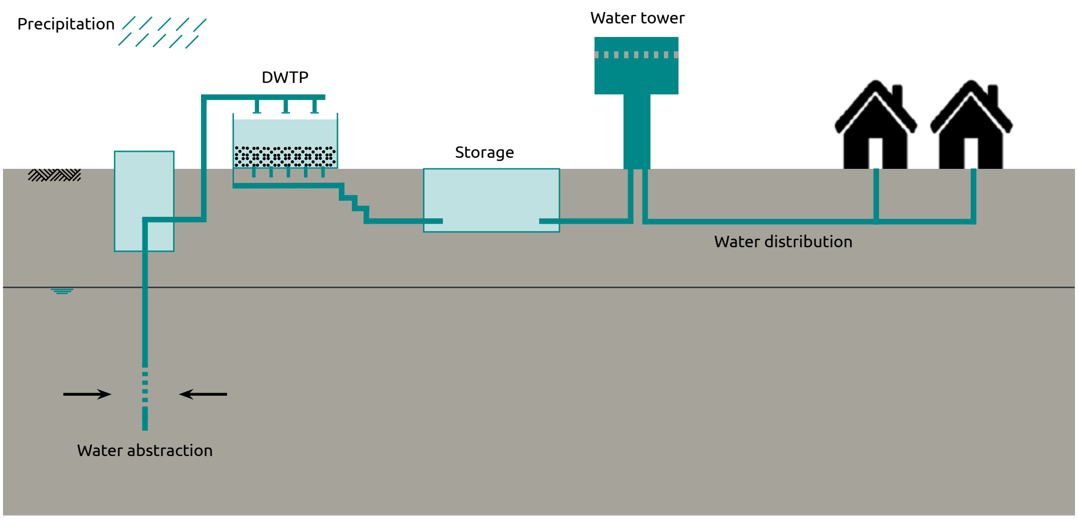


Figure 2.4: Visualisation of a drinking water supply system

2.2.3. Comparison of underground water infrastructure

Sewer systems and water distribution networks are both underground water infrastructure and have multiple similarities. However, there are also contradictions between the system's characteristics that may influence the probability and consequences of failure. Differences are explained below (Meijer et al., 2020).

1. Pressurised – gravity system: The water distribution network is a pressurised network, in contrast to the sewer system, which is a combination of gravity and pressurised system. In case of failure, a pressurised network can lead to flushing of soil around the leakage and flooding of the area. In a gravity system, soil flushes away on a normal angle.

2. Water quality: Water that is transported by the water distribution network has a sufficient water quality and can be used by costumers as drinking water (in The Netherlands). In case of leakage in the water distribution network, water gets infected and can cause health risks for users. The sewage contains contaminated water and should be treated before entering open waters. A leakage in the sewer system could lead to serious environmental problems and health risks.

3. Demand – supply driven: A water distribution network is a demand-driven system, meaning a distributed flow from one point to multiple households. Opposed, sewer systems are supply-driven systems. Sewage water flows from multiple households to one location, where it will be treated in the WWTP.

4. Location, depth and conduit size: Conduits are located under street sections, although the exact location and thus the impact differs, see Figure 2.5. As the sewer system mainly consists of a gravity system, the conduit depth is variable and may be below the water distribution network. Finally, the size and material of the conduits can be different as well.

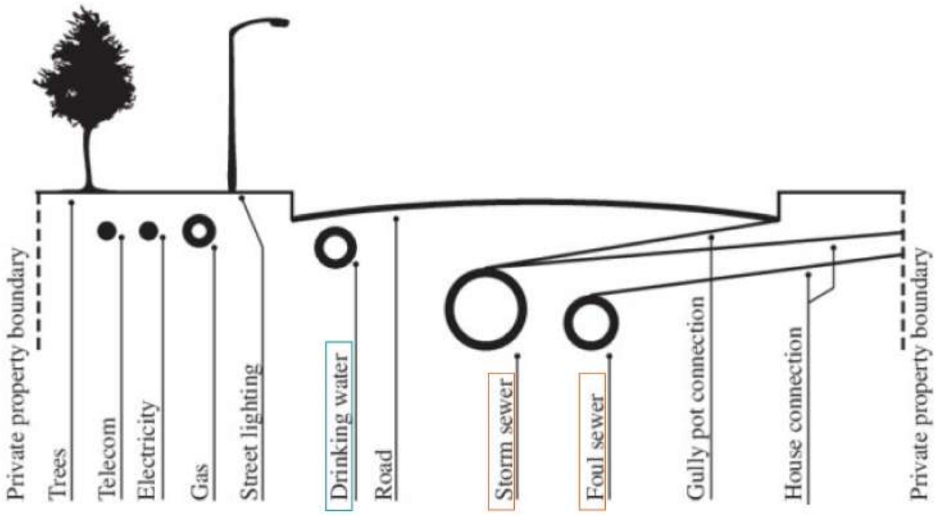


Figure 2.5: Underground infrastructure in a typical Dutch street (Van Riel, 2016)

2.3. Failure mechanisms of underground water infrastructure

In this section, failure mechanisms for both the sewer systems and the water distribution networks are explained. Subsequently, the formation of sinkholes is described in Section 2.3.2.

2.3.1. Failure mechanisms

Underground water infrastructures are difficult to manage continuously. Therefore failure is not uncommon in these types of infrastructure. Failure of underground water infrastructure could occur due to, for example, ageing or human errors. Within this research, three failure mechanisms are distinguished:

1. Structural sewer failure
2. Hydraulic sewer failure
3. Water distribution network failure

For sewer systems, a distinction is made between structural and hydraulic failure. Structural failure can be described as partial or complete loss of the load-carrying capacity. In this type of failure, the conduit is no longer intact. Hydraulic sewer failure occurs when a system does not meet serviceability requirements concerning system performance (Stanic et al., 2014). In other words, due to internal failure, the sewers do not fulfil their task in draining the water from A to B. Instead, wastewater could flow on streets. In general, hydraulic sewer failure does not lead to a total breakdown of the network. Examples of sewer failure causes are described in Appendix A. In this research, both failure mechanisms are studied separately, as both failure mechanisms lead to different failure consequences and thus have a different risk assessment.

For water distribution networks, hydraulic failure can be caused by an under or overpressure in the network. In this research, only the failure in case of overpressure is taken into account. Moreover, it is assumed that hydraulic failure (caused by overpressure) and mechanical failure occur simultaneously. In other words, when a hydraulic failure occurs, the conduit collapses. Therefore, no distinction is made between failure mechanisms in water distribution networks.

2.3.2. Formation of sinkholes

Sinkholes are pits open in the soil surface, caused by a collapse of the surface layer. Two main processes of sinkhole formation can be distinguished: natural or artificial. This study focuses on artificial sinkholes. Artificial sinkholes are created when, among others, a conduit of the water distribution network fails or a sewer conduit fails structurally. In urban areas, conduit leakage may weaken, erode and remove soil that is supporting the pipe. If water enters the soil, or bedrock enters conduits, it may flow over some distance trough the soil packed along the conduit (Kohl, 2001). The total amount of soil removal depends on time, leaking volume, pressure and material type (Kohl, 2001). These artificial sinkholes are characterised as cover-collapse sinkholes (USGS, nd).

In sewer systems, internal erosion can create voids and tunnels. Subsequently, water starts flowing faster, making soil even more erosive and creating space for soils to wash into. A visualisation of the formation of this type of sinkholes is given in Figure 2.6. The final collapse may be sudden, especially if water flows to cavities in the underlying rock (Kohl, 2001). However, there may be warning signs before the collapse such as emerging water at the surface, cracks in structures or leaning fences or trees (Kohl, 2001).

In a water distribution network, sinkholes often appear suddenly. For example, due to overpressure in the system or when excavation works hit the piped system. In this case, water flows out freely, resulting in significant water flows that flush away the soil. Subsequently, soil loses its stability and collapses.

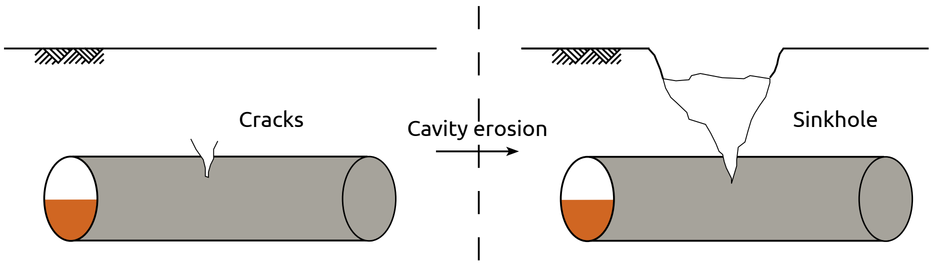


Figure 2.6: Formation of sinkholes in sewer systems, adapted from Karoui et al. (2018)

2.4. Interpretation of risk

Almost all activities in life are characterised by some level of risk. The concept of risk can have multiple meanings. Two definitions are given in the Oxford dictionary: 1) A situation involving exposure to danger; 2) The possibility that something unpleasant will happen (Oxford University Press, 2020). The first definition focuses on the consequences, the second on the probability. However, quantifying and evaluating risks merely based on the probability or consequences is less realistic (Jonkman et al., 2018). For example, the risk of losing €10 with a probability of 50% differs from the risk of losing €100 with the same probability. Besides, losing €10 with a probability of 50% is different than losing the same amount of money with a probability of 75%. The definition used in this study considers risk as to the probability of an undesired event multiplied by the consequences. Moreover, the expected value (E(d)) for a set of multiple scenarios can be expressed with the following equation:

$$E(d) = \sum_{s_i=1}^{n} p_i d_i \tag{2.1}$$

with:

p	= Probability		[1/year]
d	= Consequence		[€]

Using this definition, risk depends on both the probability and the consequences. Generally, the likelihood of an undesired event is expressed by the probability per unit time (Jonkman et al., 2018). The consequences can be multi-dimensional and can consist of different types of consequences such as damage to the environment, ecological damages, injuries and fatalities. In engineering applications, consequences are often expressed using monetary value. When the probability and consequences of risk are combined, the unit then becomes monetary value per unit time, for example, €/year. The following subsections elaborate on the probability and consequences in case of failure in the underground water infrastructure.

2.4.1. Probability of failure

The probability of failure is an essential factor in the decision process for the replacement of conduits. A high failure probability often leads to maintenance or renewal of conduits. For sewer systems, inspections determine the current state of the network, such as the CCTV. More and more, new techniques are developed to estimate the state of the conduits continuously. However, continuous measuring of conduit states and their probability of failure is still rare. Therefore, for water distribution networks, the failure frequency is often used to determine the probability of failure (KWR, nd). The failure frequency can be traced from registrations of failure events in the past. This frequency is translated to a probability of failure per kilometre conduit per year. The probability of failure for water distribution networks can be subdivided per material type. Conduits consisting of AC have a failure frequency of 0.1 per km per year, and PVC pipes have a failure frequency of 0.02 per km per year (Jacobs, personal communication, 3rd February 2020).

For sewer systems, the likelihood of failure depends, among others, on the conduit diameter, length and depth. Savic et al. (2006) found that for sewer systems in the UK, the failure probability increases with a decreasing conduit diameter. Secondly, there is an inverse relationship between the conduit length and the number of failures. Moreover, it was found by multiple studies that the failure probability of conduits increases with a decreasing cover depth (Davies et al., 2001, Fenner et al., 2000). This may be due to the influence of surface factors such as road traffic and maintenance activities. The likelihood of failure for a specific sewer system can be determined using inspections and an ageing model. According to two case studies in Haarlem and Breda, the failure frequency due to blockage of sewer conduits ranges from 0.001 to 0.01 per km per year (ten Veldhuis et al., 2011).

2.4.2. Consequences of failure

The location of conduits plays an essential role in the risk inventory to determine the consequences. Due to the crowded urban areas and all-growing infrastructure, there are several types of failure consequences. Examples are supply outage, accidents and travel delays. The complete list of consequences found in the literature is presented in Table 2.1. Several categories are shown, divided into subcategories.

This study focuses on five types of consequences. The consequences taken into account can be assessed using hydraulic modelling and (open) classified data, see research question 2 in Section 1.3. Besides, consequences can be quantified and investigated in a specific period within the research. The five categories include 1) Damage to buildings; 2) Traffic obstruction; 3) Impact on human health; 4) Costs of conduit reconstruction; 5) Drinking water supply outage. It must be noted that other factors might have a significant impact, yet they are excluded from this research.

Table 2.1: Possible consequences of underground water network conduit failure

Category	**Subcategory**
Access redundancy	Travel delay (neighbourhood)
	Travel delay (transport sector)
Damage to buildings	Housing
	Religious building
	Hospital
	Education building
	Shopping centre
	Industry
	Foster homes
	Government building
Damage to environment	Soil stability
	Disturbance of the ecosystem
	Water quality of water supply
	Water quality of waterways
	Water quality of ground water
Health impact	Chronic illness
	Gastrointestinal diseases
	Accidents
Damage to infrastructure	Bicycle path
	Main road (pavement / asphalt)
	Local road (pavement / asphalt)
	Sidewalk
	Railway
	Bridges
	Road objects such as lampposts, trees and vehicles
	Recreational area
	Parking space
	Garden / Park
Lost drinking water	Costs of lost water
	Substitution of drinking water
	Limited/no water pressure
Nuisance	Vermin
	Visual nuisance
	Noise pollution
	Odour nuisance
Reconstruction costs	Workers costs
	Material costs
Social impact	Notifications of inhabitants
	Negative publicity
	Resign of politicians
Damage to underground infrastructure	Foundation of buildings
	Television network
	District heating
	Electricity network
	Internet network
	Fibre optic cable
	Water distribution network
	Sewer system
	Basements

2.5. Determination of consequences

Previous research on failure consequences focused more on empirical data rather than predicting consequences. For example, Piratla et al. (2015) performed an empirical analysis on the main failure consequences, where 11 cases where used to estimate the (division of) total costs in case of water distribution network failure. In the following subsections, existing methods to determine consequences are discussed. Only consequences taken into account within this research are discussed, see Section 2.4.2.

2.5.1. Damage to buildings

Failure of underground water infrastructure could damage the surrounded area, including buildings. The extent of damages to buildings can be determined using several methods, based on the (empirical) costs of damages. For example, the STOWA 'waterschadeschatter' can be used. Here, the relation between the failure of conduits and damage caused to buildings, infrastructure and crops are established (STOWA, 2018). Per category, for example per building use, the direct and indirect costs of damages are determined (minimum, average and maximum costs). Another method to determine the amount of damage is by the capital value for individual buildings, as stated in the WOZ-value (Waardering Onroerende Zaken). The advantage of using a capital value as an indicator is that it is quantifiable and thus can be universally compared. However, there are often uncertainties in estimated costs, resulting in wide ranges.

Another method to determine the damage to buildings is described by the KWR. In 2011, KWR conducted a study on the effects of sinkholes in case of failure (Daal et al., 2011). The dimensions of sinkholes were estimated using the calculation method NEN3651 (Daal et al., 2011). A Geographical Information System (GIS) was used to visualise the sinkhole. This information is used for spatial analysis, to investigate the number of buildings damaged. In combination with the probability of failure, critical elements in the water distribution network could be determined.

2.5.2. Traffic obstruction

The impact of road blocks due to the failure of underground water infrastructure depends on the location of the failure within the street and the urban area. The total impact can be determined using various methods, such as detour routes, detour time and road type. Multiple studies used weighting factors to rank conduits, which are applied based on their importance and/or capital value. For example, Tscheikner-Gratl et al. (2016) determined the total priority of street sections, based on the priority of sewers, the water distribution network and the road network. Factors of vulnerability, capital value and structural resiliency were used to determine the priority of street sections.

Secondly, the impact on traffic can be calculated by the costs resulting from traffic delays or detours. For example, Piratla et al. (2015) estimated the total costs of traffic delay by using Average Annual Daily Trips (AADT), the estimated amount of trips per hour during the repair, the hourly operational costs of a vehicle, passengers per vehicle, and the detour time. A disadvantage of this method is that averages are used. Moreover, in neighbourhood levels, detour routes take less than five minutes and depend on the flow direction (from A to B or from B to A), because of one-way traffic.

Another way of calculating the traffic impact is by calculating the detour time, with the application of traffic models. Depending on the size and duration of the repair works, there can be looked at detour routes, in combination with effects of the choice of transportation, for example, train instead of car usage (van Nes, personal communication, 20th February 2020). Models often use average daily usage and can be applied to large traffic flows (>50km/h).

2.5.3. Impact on human health

Heavy precipitation, events in combination with in-sewer defects, can lead to water on streets, as sewer systems are not able to properly drain the water. Rainwater on streets can be contaminated with excretions of animals and human enteric pathogens from urban wastewater systems as well as pathogens that are naturally present in the (urban) environment. De Man (2014) studied the presence and concentrations of pathogens with flooded areas of at least $100m^2$. Samples were taken during flood events, in areas with combined and separate sewer systems, as well as surface waters. Several pathogens were tested, which account for the majority of gastrointestinal illnesses in The Netherlands (De Man, 2014, De Wit et al., 2001). People get in contact with water on the streets, for example, if they walk through the water or if they got wet from passing cars. They may ingest this contaminated water, for instance, as they touch their mouths with wet hands. Results of the infection risk are presented in Table 2.2. It was found that for combined sewer systems, the average probability of infection for adults is 3.9% per flooding event. For children, this probability is almost ten times higher and amounts to 33%.

Table 2.2: Infection risks for exposure to water on streets (De Man, 2014)

Category	Combined sewer system	Separate sewer system	Rainfall runoff
Adults	3.9%	0.58%	0.039%
Children	33%	23%	3.5%

Van Bijnen et al. (2018) studied the health risks using flood frequencies in two catchment areas in The Netherlands: Tuindorp and Loenen. In-sewer defects may cause increased pluvial flooding, resulting in an increased health risk. For three different threshold areas (50, 75 and 100m^2), flood frequencies were calculated per manhole. It was found that sediment deposits in sewer systems significantly enlarge the probability of infection due to flooding. Furthermore, the infection probability depends on sewer systems characteristics and varies within the studied catchments (Van Bijnen et al., 2018).

2.5.4. Costs of conduit reconstruction

The costs of repairing failed conduits are likely to be higher than performing maintenance to the system, due to, among others, the urgency of repairing. Piratla et al. (2015) estimated repair costs as the sum of purchases and transportation of material, worker salaries, fringe benefits and additional charges.

Besides, empirical data can be used to estimate costs for repair and return to service. The municipality of Utrecht provided a list of sewer failure events on neighbourhood level for three years (2017 – 2019). The total number of notifications was 64, of which 16 cases of system failure and 19 water on streets events. Notifications for failure are categorised as 'not able to drain', or 'manhole/drainage outlet cover is missing'. From the 16 cases of system failure, 14 regarded failure at home connections and needed relatively minor interventions. The data shows that no structural or hydraulic failure occurred in the main sewers. For these 16 cases, repair costs are known. Costs included a digging team, mini-excavator, material costs and fixed costs per notification. Prices are calculated as the fixed costs (notification) plus the variable costs (workers and material) multiplied by the duration of the repair. The average costs per failure event were €470.

2.5.5. Drinking water supply outage

Drinking water companies want to supply 100% of the drinking water demand, even in stressed situations with limited water pressure due to, for example, leakage or breakage of conduits. Hence, water distribution networks are designed for robustness, using large pipe diameters and looped networks (Blokker et al., 2018). Despite this, the failure of segments caused by pipe breaks regularly occurs in drinking water distribution networks. Failure of one section leads to the outflow of drinking water and under pressure in the network, which affects the supply to households and business users.

Several methods can be used to determine the effects of drinking water supply outage. Piratla et al. (2015) estimated the lost product in case of conduit failure, the costs of supply outage and costs of substitution of water. Prices are based on the estimated amount of water consumption and alternative water sources during supply outage. In the Netherlands, the average water usage per person is 120l/d, and average households consist of 2.1 persons. Using these key figures, the average water usage per household is around 92m^3/y. This results in lost revenues of €0.02 per household in case of failure.

In the Netherlands, the method of 'Ondermaatse Leveringsminuten' (OLM) is often used as an indicator for the functioning of a network. The OLM is defined as the average time per year in which costumers do not have access to (sufficient) water supply (Kiwa, 2005). Duration of supply outage and the affected customers are determined for all interruptions in water supply, including repair works and maintenance. For example, the average network OLM of Vitens was 19.45min in 2018 (Vitens, 2018).

3

Methodology

In order to determine the consequences of failure, this chapter discusses the methods and materials used within this research. The objective is to answer the second research question: 'How can the consequences of failure be assessed, using hydraulic modelling and (open) classified data?' First, a description of the case study is given, including the reference method, in Section 3.1. The calculation method of the affected area is presented in Section 3.2. Section 3.3 describes methods to determine the five failure consequences: damage to buildings, traffic obstruction, impact on human health, costs of conduit reconstruction and drinking water supply outage.

3.1. Study area

A research catchment is used to test the development process and to ensure that the methodology could be readily deployed. An area that has previously been studied is chosen as a case study, because of the data availability and comparability (Dirksen, 2013, Meijer et al., 2020, 2018, Van Bijnen et al., 2018). The study is conducted in Tuindorp in the municipality of Utrecht. An impression of the study area is presented in Figure 3.1. The study location has a flat catchment area of approximately 400ha, with 10,656 inhabitants (Van Bijnen et al., 2018). The neighbourhood is built in the 1930s as a so-called 'garden village', with spaces for green in a compact area (Canon van Nederland, nd).

Figure 3.1: Impression of the study area, Tuindorp. December, 2019

The tuindorp study area has a combined sewer system constructed in the 1970s as a looped gravity flow system (Van Bijnen et al., 2018). The collected sewage is transported to the pumping station in the southern part of the catchment. Besides, the sewer system contains five CSO structures. The water distribution network contains transportation and distribution conduits with the oldest pipes dating from 1896 (in 2014). The drinking water company operating in this area is Vitens. Figure 3.2 shows the location of the study area within the city of Utrecht. Details about the characteristics of the sewer system and water distribution network are given in Table 3.1 and 3.2 respectively. For the sewer system, 74% of the conduits has a diameter between 200 and 300mm. The total length of the network is 28km, and segment lengths are between 3 and 85m. The average depth increases with an increasing diameter from 1.3 to 2.9m below ground level. The water distribution network contains conduits with diameters ranging from 20 up to 710mm. Total network length is 47.5km, with variable segment lengths ranging from 0.1 to 441.5m. The depth of the conduits in Tuindorp is 1m below ground level.

Within this research, open data and data assessed via the municipality of Utrecht, earlier research and the drinking water company is used. Information on data used can be found in Appendix B.

Table 3.1: Main characteristics of the Tuindorp sewer system

Conduit diameter [mm]	**Total length [m]**	**Segment length [m]**	**Depth [m]**	**Average depth [m]**
150 - 200	229 (1%)	13 - 56.3	1.25 - 1.43	1.33
200 - 300	20748 (74%)	1.41 - 66.65	0.60 - 2.60	1.84
400 - 600	5228 (19%)	2.83 - 72.11	1.25 - 3.61	2.35
700 - 900	1869 (7%)	7.07 - 84.86	2.08 - 3.95	2.71
1000 - 1600	146 (1%)	3 - 47.01	1.73 - 3.29	2.89

Table 3.2: Main characteristics of the Tuindorp water distribution network

Conduit diameter [mm]	**Total length [m]**	**Segment length [m]**
20 - 60	8022 (17%)	0.25 - 251.09
80 - 100	20407 (43%)	0.10 - 254.36
101 - 200	12883 (27%)	0.23 - 210.15
201 - 400	2456 (5%)	0.45 - 441.47
401 - 710	3628 (8%)	0.46 - 330.96

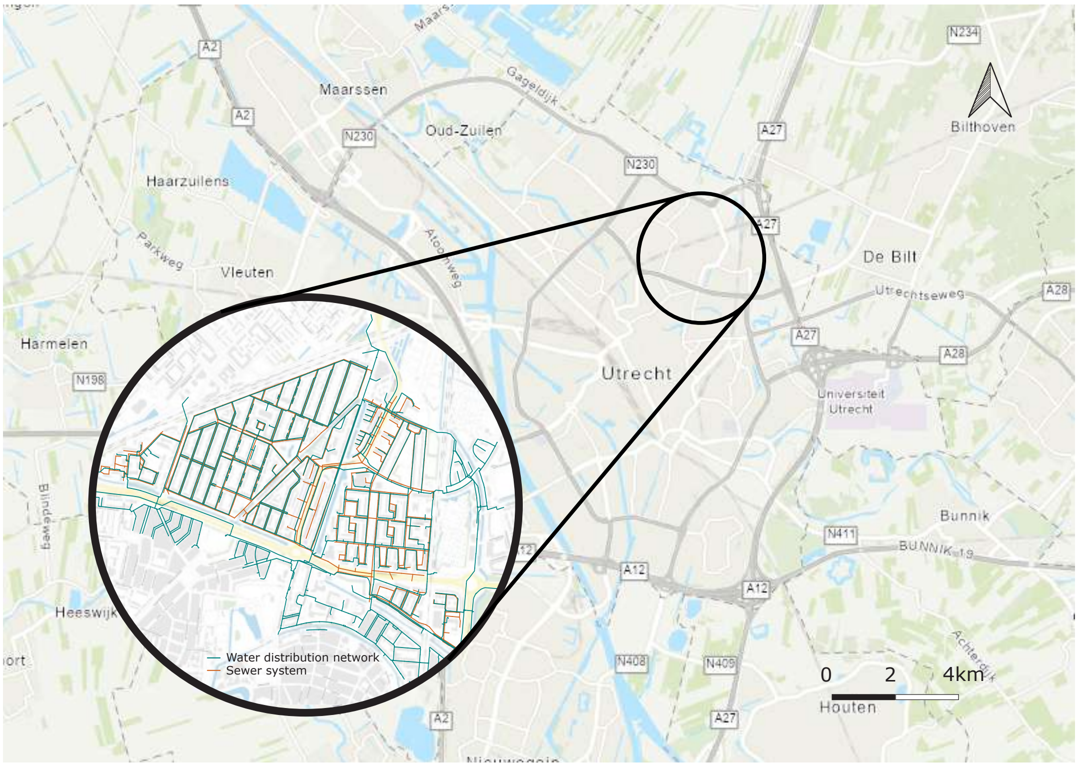


Figure 3.2: Overview of the study area in Utrecht with a closeup of Tuindorp. The catchment layout is indicated in the closeup.

Hydraulic functioning of the networks (reference method)

As stated in Section 1.3 the criticality of segments, according to the hydraulic functioning, is used as a reference for the consequences of failure. Meijer et al. (2018) and Meijer et al. (2020) developed a method to determine critical elements in sewer and drinking water networks, which can be used to guide asset management. For the ranking of the elements, the hydraulic functioning of the networks is studied with the use of a Graph Theory-based method (GTM) (Meijer et al., 2018) (Meijer et al., 2020). Graphs are used to simplify underground water infrastructure and its connectivity in nodes and links. This method takes into account the effects of the failure of individual elements on the functioning of a system as a whole. Elements are ranked according to their impact on the functioning of the system. The main advantage of this method is that large hydrodynamic model calculations are avoided since the main starting point is the structure of the network (Meijer et al., 2018). For the water distribution network, the degree of conduit criticality is determined based on the pressure loss in case of failure, when valves are open. Results retrieved are presented in Figures 3.3 and 3.4. The degree of criticality ranges from 0 (less important) to 1 (most important). For sewer systems, it is found that conduits with large diameters and dead-end conduits are most critical.

The outcomes of the individual consequences (Section 3.3) will be compared with the results of the hydraulic network functioning to answer the main question. Normalised values are used to determine the overlap of the outcomes. The Kendall rank correlation coefficient can be used to determine the degree of association between the rate of criticality for hydraulic performance and the different consequences of failure. Kendall's Tau a non-parametric measure of relationships between columns of ranked data (Kendall, 1945). The correlation factor varies between -1 and 1. A factor -1 implies a 100% negative relation and factor 1 a 100% positive relation between the outcomes. A coefficient of 0 indicates that there is no relation between the results. The correlation coefficient (τ_b) can be calculated according to the following equation:

$$\tau_b = \frac{P - Q}{(\sqrt{P + Q + X_0} \cdot \sqrt{P + Q + Y_0})} \tag{3.1}$$

with:

P	= The number of concordant pairs	[-]
Q	= The number of discordant pairs	[-]
X_0	= The number of pairs tied only in X	[-]
Y_0	= The number of pairs tied only in Y	[-]

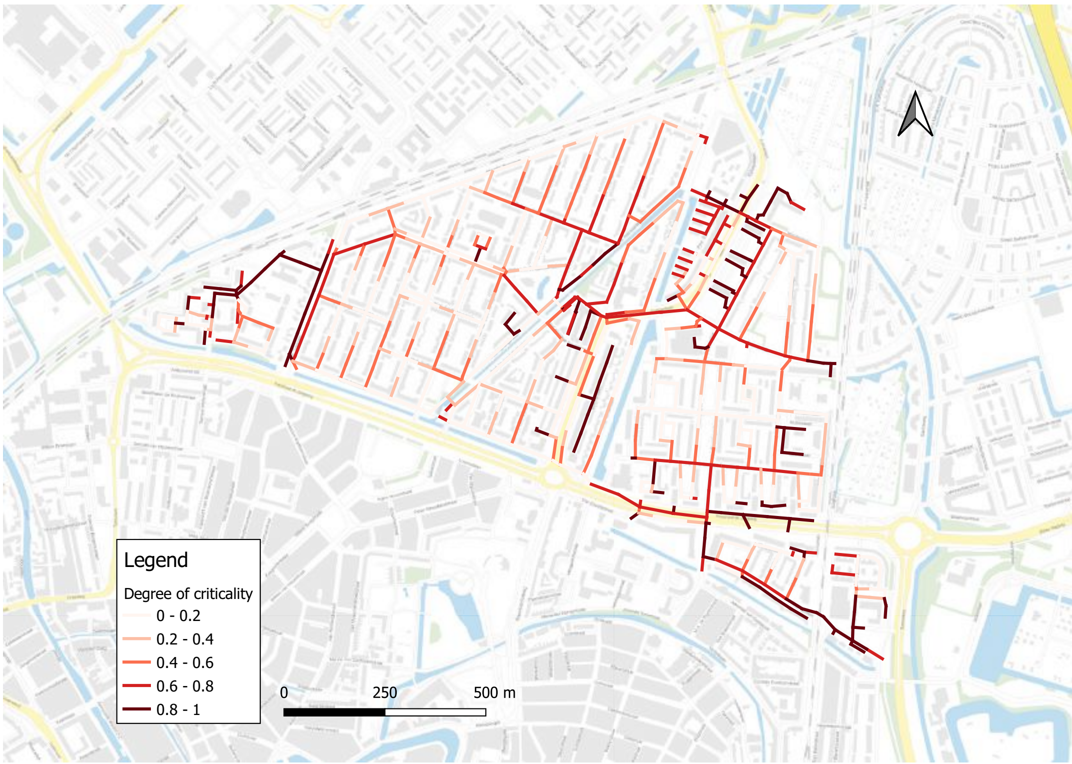


Figure 3.3: Rate of criticality from 0 (less critical) to 1 (most critical), for hydraulic functioning in the sewer network, adapted from Meijer et al. (2018)

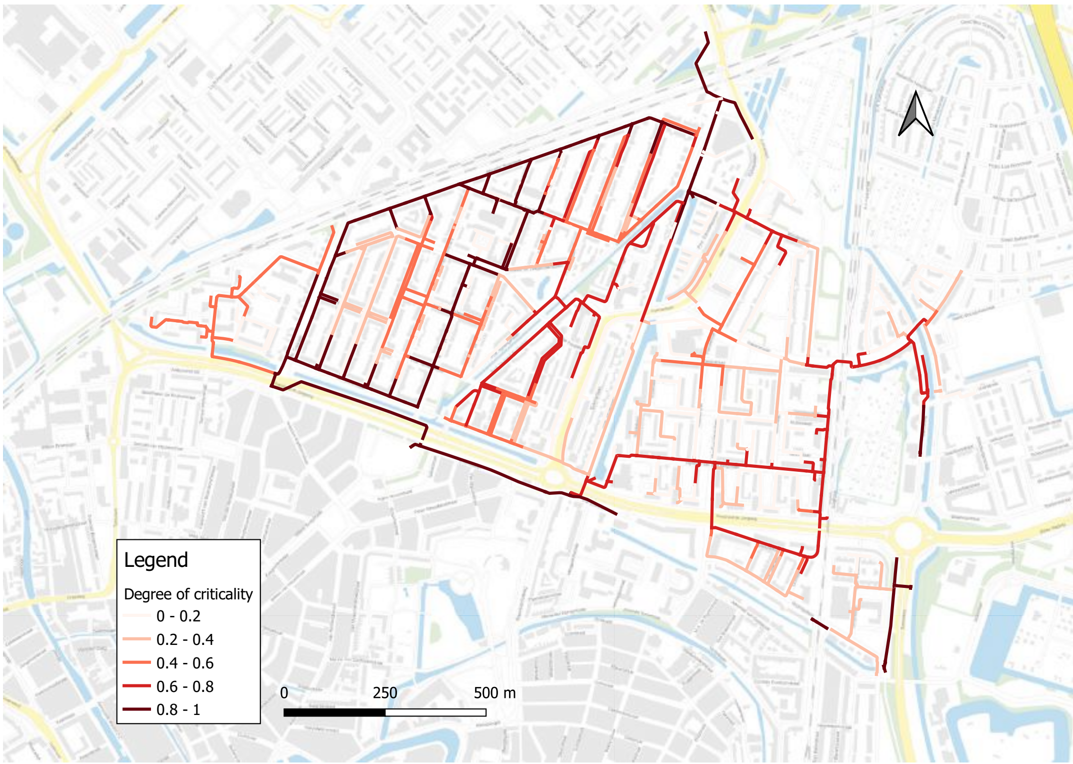


Figure 3.4: Rate of criticality from 0 (less critical) to 1 (most critical), for hydraulic functioning when valves are open in case of water distribution network failure, adapted from Meijer et al. (2020)

3.2. Affected area caused by underground water infrastructure failure

In order to define the consequences of failure, the first step is to understand the affected area in case of underground water infrastructure failure. Two different types are described: flooded area (Section 3.2.1) and sinkhole formation (Section 3.2.2). Table 3.3 presents the occurrence per failure type.

Table 3.3: Affected area per failure mechanism

Category	**Sewer system - structural failure**	**Sewer system - hydraulic failure**	**Water distribution network**
Exposure of the flooded area	x	✓	✓
Exposure to sinkhole formation	✓	x	✓

3.2.1. Flooded area

A modelling study is applied to achieve a better understanding of water flows induced by the failure of underground water systems. Two models are conducted: 1) hydraulic sewer failure and 2) water distribution network failure. In this section, a brief description of the modelling steps is given. A schematisation of the steps involved in the simulation of the flooded area is presented in Figure 3.5. First, the model settings for both the sewer system and water distribution network are elaborated on. Subsequently, the determination of the computational grid is explained. The model outputs of the area of flooding can be used for further analysis of the consequences of failure. More information about the software used to determine the affected area can be found in Appendix C.

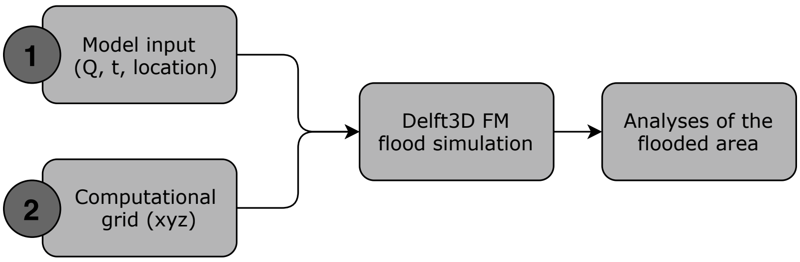


Figure 3.5: General Delft3D FM model approach to determine the flooded area

1. Model input

To explore the water flows in case of conduit failure, two model scenarios have been created: hydraulic sewer failure and water distribution network failure. The Delft3D FM model requires input files that contain information about the duration of leakage, location and discharge. Input values for the model scenarios are presented in Table 3.4. The settings are further explained below, per failure type. Additionally, the main Delft3D FM model settings are presented in Appendix D.

Table 3.4: Model settings per failure mechanism

Category	**Sewer system - hydraulic failure**	**Water distribution network**
Location of outflow (x,y)	manhole	middle of conduit
Location drainage (x,y)	-	gully pots
Outflow rate [m^3/s]	0.01	0.0007 - 0.79
Discharge drainage [m^3/s]	-	0.003
Time of outflow [min]	25	60
Total run time [min]	60	60

Sewer system

In-sewer defects may lead to flooding at several manholes. Meijer et al. (2018) studied the impact of individual conduit defects on the flooding of manholes. Stationary design storms were used to determine the number of manholes flooded. In this study, the number of manholes flooded per individual conduit defect is determined by a design storm of 60l/s.ha. Subsequently, in the Delft3D FM model, the coordinates of the manholes are used as the location(s) of leakage. Furthermore, it is assumed that the sewer system is blocked, including the nearest gully pots. Hence, water flows on the street and can not be drained.

The outflow (or: discharge of leakage) is determined using a flood volume, spread over a specific period. The research of Van Bijnen (2018) and SOBEK models are used to estimate the flood volume at manholes. According to Van Bijnen (2018), the flood volume can be simulated as a ‘cone’ on top of a manhole (Figure3.6). The flooded area ($A_{floodable}$) is the total area available for the storage of floodwater at a specific node. The maximum flooded area is set at 100m^2 (De Man, 2014). The threshold level for the flood depth is limited to 0.15m to avoid levels above the sidewalks (Van Bijnen, 2018). This leads to a total flood volume of 15m^3.

Subsequently, to validate the flood volume of 15m^3, SOBEK models are used. In SOBEK, flooding is simulated by using standard precipitation events (Vlaamse composiet buien (VLC)). VLC with a return period of 1, 2, 5 and 10 years are used. Results of the analyses are presented in Appendix E. It is found that flood volume at manholes range between 0-6.5m^3 for a one year return period and between 0-50.0m^3 for a return period ten years. It is found that the 15m^3 flood volume is in line with a precipitation event with a return period of 10 years.

A sensitivity analysis is performed on the flood volume to investigate the relation between flood volume and the flooded area. Flood volumes of 7.5, 30 and 150m^3 are used in this analysis.

The model is run for a simulation period 60min. The outflow period is limited to 25min, such that the outflow rate becomes 0.01m^3/s. Afterwards, the model runs for another 35min to permit water flows.

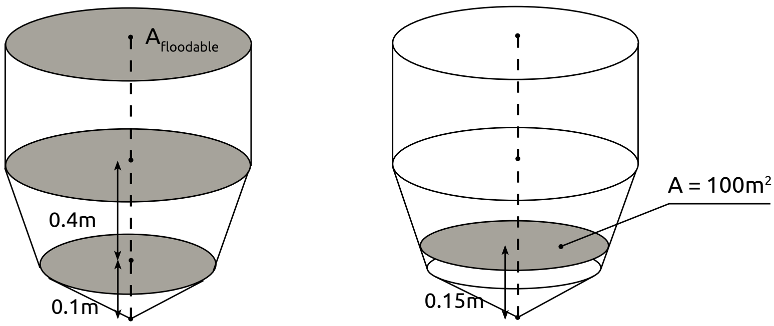


Figure 3.6: Flood cone on top of a manhole to store water above street level, based on Van Bijnen (2018)

Water distribution network

In case of water distribution network failure, the flooded area is modelled using one point of leakage per conduit. The point of leakage is located in the middle of a conduit section, with an outflow rate depending on the conduit diameter. It is assumed that gully pots are working properly within this scenario. Therefore, gully pots are present in this system to drain flood water towards the WWTP. Per conduit failure, gully pots within the radius of 100m are taken into account to drain the water.

The discharge of leakage can be determined using the outflow velocity and diameter of the conduit. It is assumed that there is a free outflow of water and that there is no pressure loss in case of failure (Jacobs, personal communication, 3rd February 2020). The outflow velocity is higher than the velocity in the water network (0.2 - 0.6m/s). According to Jacobs (personal communication, 3rd February 2020), the outflow rate is 2.0m/s. The total discharge per conduit can be determined according to Equation 3.2. In Tuindorp, the average discharge is 0.04m^3/s, with a minimum of 0.001 and a maximum of 0.79m^3/s.

The drainage capacity of gully pots is determined to be 3.0l/s, assuming that sewers can drain the total flood volume. This assumption is valid for the sewer system in Tuindorp, as sewer can drain at least 18l/s.

$$Q = (\frac{1}{4} \cdot \pi \cdot d^2) \cdot v \tag{3.2}$$

with:

Q	= Discharge		[m^3/s]
d	= Internal diameter		[m]
v	= Outflow water velocity		[m/s]

The total amount of lost water depends on the duration of leakage. In other words, it is based on the time between failure and turning off the water supply. The average time of leakage is 60min (Jacobs, personal communication, 3rd February 2020). This is divided over 30min between failure and notification of the failure and 30min from notification and closing of the system. In Delft3D FM, the model is run for a simulation period of 60min.

2. Computational grid

To simulate flow in the Delft3D FM model, a grid consisting of elevation values is required. Maps of the 'Actueel Hoogtebestand Nederland' (AHN) are used and adapted to produce the digital elevation model (DEM). In this study, the AHN3 raster Digital Terrain Model (DTM) of 0.5m is used, which is produced between 2014 and 2019 (Waterschappen, Provincies and Rijkswaterstaat, 2020). The accuracy of the AHN3 is 5cm in every squared metre in The Netherlands (Waterschappen, Provincies and Rijkswaterstaat, 2020). Points classified as 'ground level' are re-sampled into a grid. Other points, such as buildings, trees and water, are excluded from re-sampling. Therefore, empty data points are filled using nearest neighbour interpolation methods. Water does not directly flow into peoples' homes, although when it reaches a certain level, it can enter. Therefore, building data from OpenStreetMap (OSM) is used to sample buildings into the elevation model. It is assumed that buildings can be flooded above a threshold level of 0.2m. Result of the elevation grid is presented in Figure 3.7.

Next, a rectangular grid is created with the dimensions of the catchment area, using a Flow Flexible Mesh Model in Delft3D FM. The elevation model is applied to the grid, where interpolation is performed using averages on the grid area. The size of the grid cells is set at 1.0m (a cell area of $1.0m^2$). In general, the number of grid cells should be limited to restrict computational time. However, the grid should cover a sufficient area to have enough resolution within the area of interest.

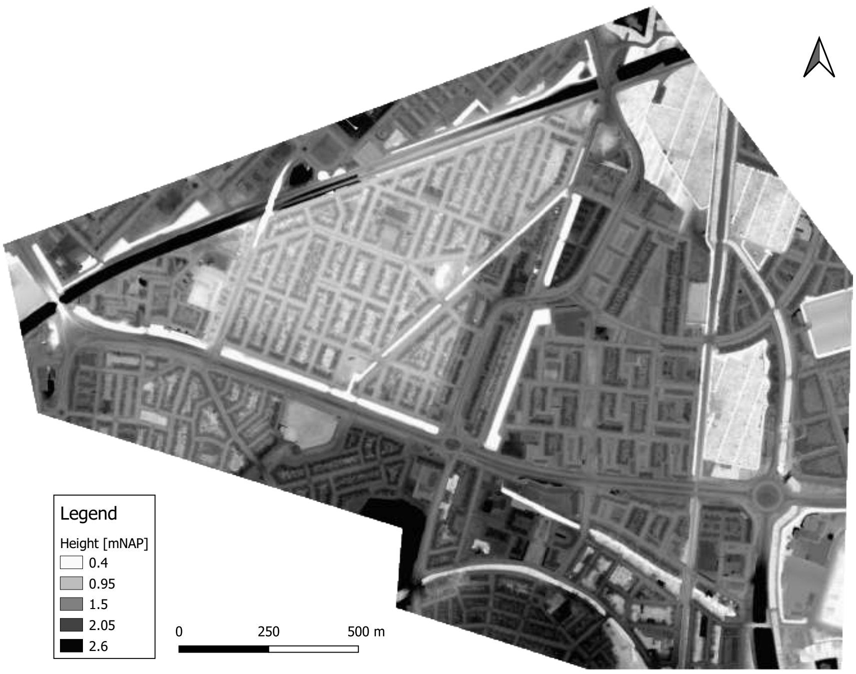


Figure 3.7: Tuindorp elevation map relative to mNAP

3.2.2. Sinkhole area

This section aims to determine exposure to sinkhole formation. Sinkholes are formed due to failure of the elements, see Section 2.3.2. Two different methods are used to calculate the area of the impact. First, the calculation method for the sewer system (structural failure) is described. Subsequently, the calculation for sinkhole formation caused by water distribution network failure is explained.

Sewer system

In case of structural sewer failure, the soil above collapses into the conduit due to the loss of structural integrity of sewer conduits completely blocking the flow of wastewater at that specific place. Furthermore, it forms a risk for the stability of the surrounding area. Sinkhole dimensions can be calculated using the slope angle and depth of the conduit. Equation 3.3 is used to determine the diameter of the sinkhole.

$$D_s = W + 2 \cdot \frac{Z}{tan(\theta)} \tag{3.3}$$

with:

D_s	= Diameter of the sinkhole	[m]
W	= External width of the conduit	[m]
Z	= Ground cover on the top of the conduit	[m]
θ	= Angle of repose	[°]

To determine the mean ground cover on top of the conduit (Z), the average depth below ground level between the beginning and the end of the conduit is used (Section 3.1).

It is assumed that the soil flushes away on a normal angle in case of structural sewer failure. Factors of influence on the angle of repose are the soil type and water content in the soil. Table 3.5 shows that slope angles range from 15° (water filled sand) up to 45° (for example crushed stone gravel) (Al-Hashemi and Baghabra Al-Amoudi, 2018). The soil type is 'anthropogenic' in the study area (Provincie Utrecht, nd). In this study, an angle of 30° is chosen, partly using it as a safety margin such that the risk inventory is on the safe side. To test the robustness of the results, a sensitivity study is performed. Here, angles of repose of 15° and 45° are evaluated.

Table 3.5: Angle of repose for different soil types, adapted from Al-Hashemi and Baghabra Al-Amoudi (2018)

Material (condition)	**Angle of repose**
Asphalt (crushed)	30 - 45°
Clay (dry lump)	25 - 40°
Granite	35 - 40°
Gravel (crushed stone)	45°
Gravel (natural with sand)	25 - 30°
Sand (dry)	34°
Sand (water filled)	15 - 30°
Sand (wet)	45 °

Water distribution network

Failure in the water distribution network leads to the outflow of waters. This water causes erosion and leads to flushing of the soil around the leak. Figure 3.8 illustrates the radius of a sinkhole, including a safety and stability zone in case of drinking water network failure. The safety zone is equal to the disturbance area (R_B) plus the stability zone. The width of the stability zone depends on soil characteristics and dimensions of the nearest structure.

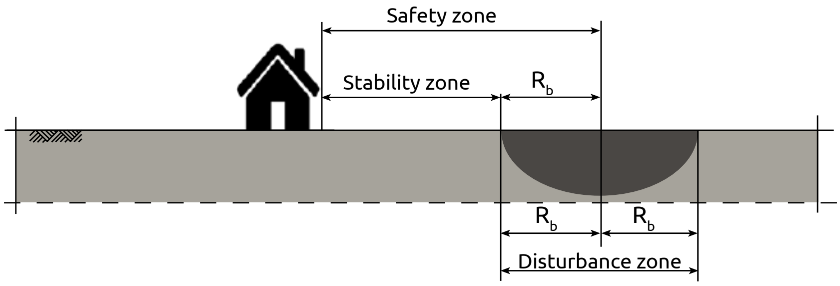


Figure 3.8: Sinkhole radius in case of water distribution network failure, adapted from NEN 3651 (2012)

The dimensions of sinkholes in case of water distribution network failure can be determined using empirical formulas. The radius of the sinkhole can be estimated using the 'calculation method from NEN 3651 (2012)' and 'evaluation of the calculation method from NEN 3651' (Mastbergen, 2010). The most accurate formula to calculate the radius of the sinkhole is given in Equation F.1 in Appendix F. Besides, main assumptions are explained in Appendix F.

For the accurate formula, requirements are the flow rate (Q) and normative pressure head (h), yet they can neither be measured nor be determined from pump characteristics in this study. Therefore, a simplified method is used to determine the sinkhole dimensions (Equation 3.4). This simplified method is based on the assumption that the pressure in the conduit at the location of leakage remains equal to the maximum operating pressure (NEN 3651, 2012). Additionally, the maximum flow is not limited by the pump capacity (NEN 3651, 2012). The decrease in data requirement is accompanied by less accurate results of the radius. The simplified equation often overestimates the real value, with results up to four times the radius calculated according to the original formula (Formula F.1) (NEN 3651, 2012). To study the uncertainty of the output, a sensitivity analysis is performed. In this analysis, the sinkhole size is reduced to a half and a quarter of the original sinkhole area.

$$R_B = 8 \cdot \sqrt[8]{h_m^3 \cdot d_i^5} \tag{3.4}$$

with

R_B	= Radius of the sinkhole	[m]
h_m	= Maximum operating pressure	[mwk]
d_i	= Internal diameter of the conduit	[m]

3.3. Consequences of underground water infrastructure failure

When the affected area in case of underground water network failure is known, it can be linked with the characteristics of the built environment. Five consequences are taken into account: damage to buildings, traffic obstruction, impact on human health, costs of conduit reconstruction and drinking water supply outage. In this section, affected area and characteristics of the built environment are directly linked to determine the consequences of failure. Table 3.6 shows the failure mechanism with the corresponding categories. The methods are explained on the basis of the case study in Tuindorp, Utrecht.

Table 3.6: Consequence categories per failure mechanism

Category	**Sewer system - structural failure**	**Sewer system - hydraulic failure**	**Water distribution network**
Damage to buildings	✓	✓	✓
Traffic obstruction	✓	✓	✓
Impact on human health	x	✓	x
Costs of conduit reconstruction	✓	x	✓
Drinking water supply outage	x	x	✓

3.3.1. Damage to buildings

Failure of conduits, both in sewer systems and water distribution networks, could damage the surrounding area. In this category, physical damage caused to buildings in the vicinity of failure is estimated. The extent of damage depends on the size of the affected area (sinkhole and flooding) and value of surrounded buildings. By determining whether the affected area (A_i) overlaps with building categories, the damage per conduit can be calculated (Equation 3.5). Damage to buildings is defined either as water damage due to flooding, or the loss of stability of buildings. It is assumed that damage occurs when the affected area hits a building. The analysis is applied to the three failure types: hydraulic sewer, structural sewer and water distribution network.

$$\text{Damage to buildings}(i) = A_i \cap \sum_{i=1}^{n} \text{Category}_i \tag{3.5}$$

A distinction in building use is made as not all the buildings - for example, church, school, housing - do have the same (capital) value (Tscheikner-Gratl et al., 2016). In this study, the function of buildings is used to determine the total damage to buildings. A distinction between 6 categories is made, based on categories as described by the KWR (Daal et al., 2011) and in the 'Bouwbesluit' (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2011). Categories for building use are shown in Table 3.7. Besides, to compare the mutual results, damages per category can be divided by the total area of that category. A distinction is made between the area for sewer systems and water distribution network, as the water distribution network covers a wider area of Tuindorp.

Table 3.7: Building categories

Category	**Description**	**Area [ha] (sewer system/ water distribution network)**
1	Commercial	1.23 / 1.7
2	Housing	19.94 / 30.84
3	Other	3.16 / 3.91
4	Public	0.52 / 0.7
5	High-risk objects	0.03 / 0.04
6	Education	2.05 / 2.20

Buildings with commercial use are characterised by the function of trading of materials, goods and services. Multiple residential building types (category 'housing') can be defined, such as apartments, (boat)houses and mobile homes. Educational buildings include primary and secondary schools, as well as universities. The category 'public buildings' includes municipalities, buildings for health care, train stations and religious buildings. 'High-risk objects' are determined by industry locations and locations with storage of flammable, explosive or toxic substances such as gas stations. Finally, the category 'other' mainly consists of sheds and garages. For the study area in Tuindorp, building uses are displayed in Figure 3.9.

The affected area (A_i) per failure type is determined as exposure to the flooded area and/or sinkhole formation (see Section 3.2). It is assumed that the flooded area causes damages when it intersects with a building, regardless of the size of the overlap. In the case of sinkhole formation, average damage over the conduit is determined. In other words, the total damage is corrected for sinkhole size. Furthermore, a sensitivity analysis is done on the affected area, as explained in Section 3.2 to identify the (in)dependency of the affected area and to test the robustness of the results.

Figure 3.9: Building use in Tuindorp

3.3.2. Traffic obstruction

Failure of underground water systems can cause road blockages, resulting in traffic delays and detours. The impact of road blockages depends on the location and duration of failure and can be calculated using several methods such as detour routes, detour time and road type (Section 2.5).

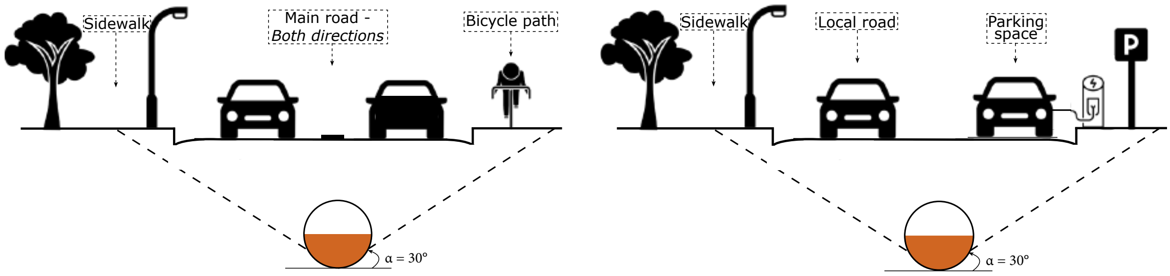
In this study, consequences regarding traffic obstruction are formulated by the function of roads, using corresponding importance factors ($Category_i$). The analysis is performed for the three failure mechanisms: structural sewer, hydraulic sewer and water distribution network. The obstructed area (A_i) is determined by the size of the sinkhole or flooded area. To calculate the traffic obstruction per pipe segment, the affected area is combined with the road network to see where they overlap. The total damage to road systems can be calculated with Equation 3.6.

$$\text{Traffic impact}(i) = A_i \cap \sum_{i=1}^{n} \text{Category}_i \tag{3.6}$$

In total, 6 categories of road types are defined, mentioned in Table 3.8. A distinction in road use is made based on OSM and Google Maps, in combination with data from the municipality of Utrecht on road usage. To compare the mutual results, damages tested against the area in which the category occurs. Areas of the different categories are presented in the rightmost column of Table 3.8. A visualisation of road use in Tuindorp is presented in Figure 3.11. Main roads are characterised by a larger economic value, and larger traffic flows, compared to local roads. A distinction is made between obstruction in one or both directions. The main roads are determined using the so-called ‘strooiroutes’. These roads are combated with salt in case of weather events that cause slippery roads. In Utrecht, the first ‘strooiroutes’ contain main roads, main cycle paths, roads to neighbourhoods and bus routes (Gemeente Utrecht, nd). In this study, cycle paths are defined in a different category. Other roads for car traffic, not classified as main road, are classified as local road. Sideways are defined as pavement only accessible for pedestrians, including paths to garages and roads in parks. Other categories are ‘railway’ and ‘parking space’. Subsequently, roads are sorted based on their impact, see column ‘sorting variable’ of Table 3.8. Hence, conduits that cause damage to the railway are sorted first, main roads (both directions) second and so forth and so on. An example of the affected area and traffic impact is given in Figure 3.10. With a similar affected area in both cases of failure, the total traffic impact in Figure 3.10a becomes higher, due to the main road that is affected.

Table 3.8: Road categories with corresponding sorting variable

Category	Description	Sorting variable	Area [ha]
1	Bicycle path	5	4.8
2	Local road	4	22.56
3a	Main road - *both directions*	2	14.88
3b	Main road - *one direction*	3	-
4	Sidewalk	6	54.88
5	Parking space	7	6.48
6	Railway	1	5.05



(a) Damages to sidewalk, main road (both directions) and bicycle path caused by a sinkhole of 30°

(b) Damages to sidewalk, local road and parking space caused by a sinkhole of 30°

Figure 3.10: Examples of infrastructure types damaged by structural sewer failure

To determine the affected area, two methods are used, respectively one for sinkhole formation and another for the flooded area. First, when a sinkhole damages roads of the categories 1, 2, 4, 5 and 6, it is assumed that the road capacity decreases with 100%. In other words, the specific road is blocked in both directions (A to B and B to A), due to the sinkhole and safety zone. However, for main roads (Category 3) a distinction is made for blockage in traffic direction. When the road is blocked from A to B, the direction from B to A may still be accessible.

Secondly, in case of flooding of the area, threshold levels are used to determine the extent of traffic impact. Thresholds are determined to see at which flood depth the roads are no longer accessible. For example, if the flood depth becomes higher as 5cm, sidewalks are blocked, however, other road types are still accessible. Threshold levels for different categories are presented in Table 3.9. Similarly as for sinkhole formation, main roads can be blocked in either one or both directions. Besides, a sensitivity analysis is performed on the threshold depth. Per category, a lower and higher threshold is set.

Table 3.9: Threshold level of the flooded area per road category

Category	Threshold flood depth [cm]	Sensitivity threshold depth [cm]
Bicycle path	10	5 - 20
Local road	20	10 - 30
Main road	20	10 - 30
Sidewalk	5	0 - 10
Parking space	10	5 - 20
Railway	20	10 - 30

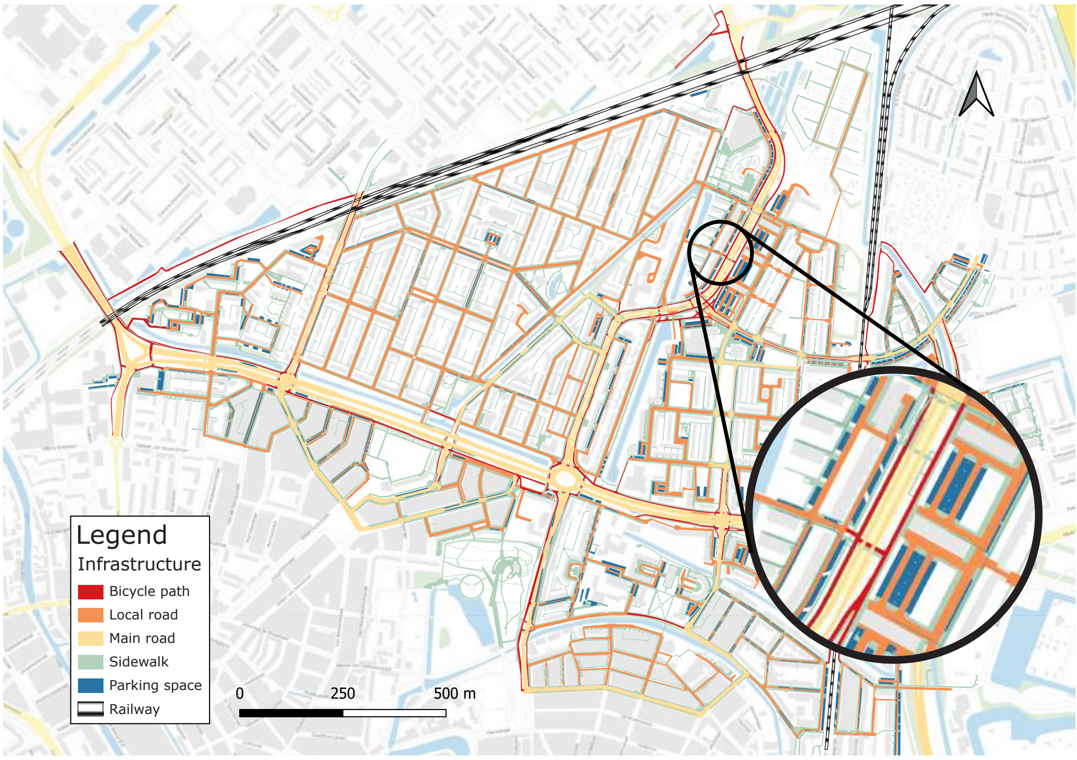


Figure 3.11: Road use in Tuindorp

3.3.3. Impact on human health

Human health can be affected due to failure in a water supply or sewer pipe. As this study only includes failure due to overpressure, only the effects of sewer system hydraulic failure is considered. In other words, the health effects caused by failure in drinking water networks are not discussed.

Extreme precipitation event, in combination with in-sewer defects, can lead to (waste)water on streets (see Section 2.5). In this study, the human health impact is determined by the number of people exposed to flooding (buffer zone) and the infection probability per person per flooding event, see Equation 3.7. De Man (2014) studied the infection risks per exposure event per person, for adults and children. As Tuindorp contains a combined sewer system, the infection risk per event is determined on 3.9% for adults and 33% for children. The spatial distribution of children in Tuindorp is visualised in Figure 3.12 (Van Bijnen et al., 2018).

$$\text{Infections} = (P_{\text{infection}} \cdot \text{people}) \cap (\text{buffer zone}) \tag{3.7}$$

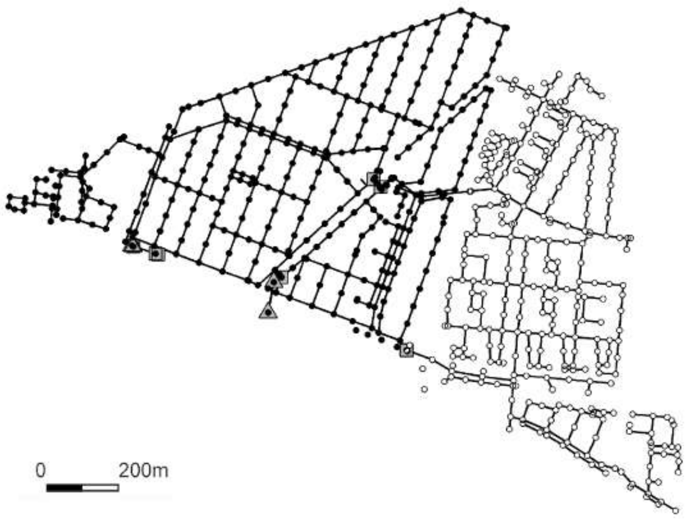


Figure 3.12: [Spatial distribution of children in Tuindorp: black dots (21%) and white dots (12%) (Van Bijnen et al., 2018)

In order to investigate the number of people exposed to flooding, the average number of inhabitants per households are used. The Netherlands consists of 7.9 million households (1st of January 2018) with an average amount of 2.1 people per household, only taking into account private housing (RIVM, nd). This is in line with the number in Tuindorp, with a total of 9930 inhabitants spread over 5090 households (Van Bijsterveld, 2020). The amount of households per building is determined by using information about addresses and buildings, as stated in the BAG (Kadaster, 2020). Outcomes are presented in Figure 3.13.

The number of people affected depends on the infection probability and the number of people living near the location of failure. A buffer zone around the flooded area is created to estimate the number of people that get in contact with the contaminated water, for example by crossing that particular street or living in that area. In this study, the assumption is made that households within 10m of the flooded area get in contact with the flood water. It is assumed that people living in the buffer area also cross that area and get in touch with the water. Other connections, for example near schools or industry, are not taken into account.

Besides, a sensitivity analysis is performed on the buffer zone and flooded area. Next to the 10m buffer, the impact of two different buffer zones of 15 and 25m are tested. Besides, the flooded area is halved and doubled in size in order to investigate the sensitivity of the flooded area on the results of the impact on human health.

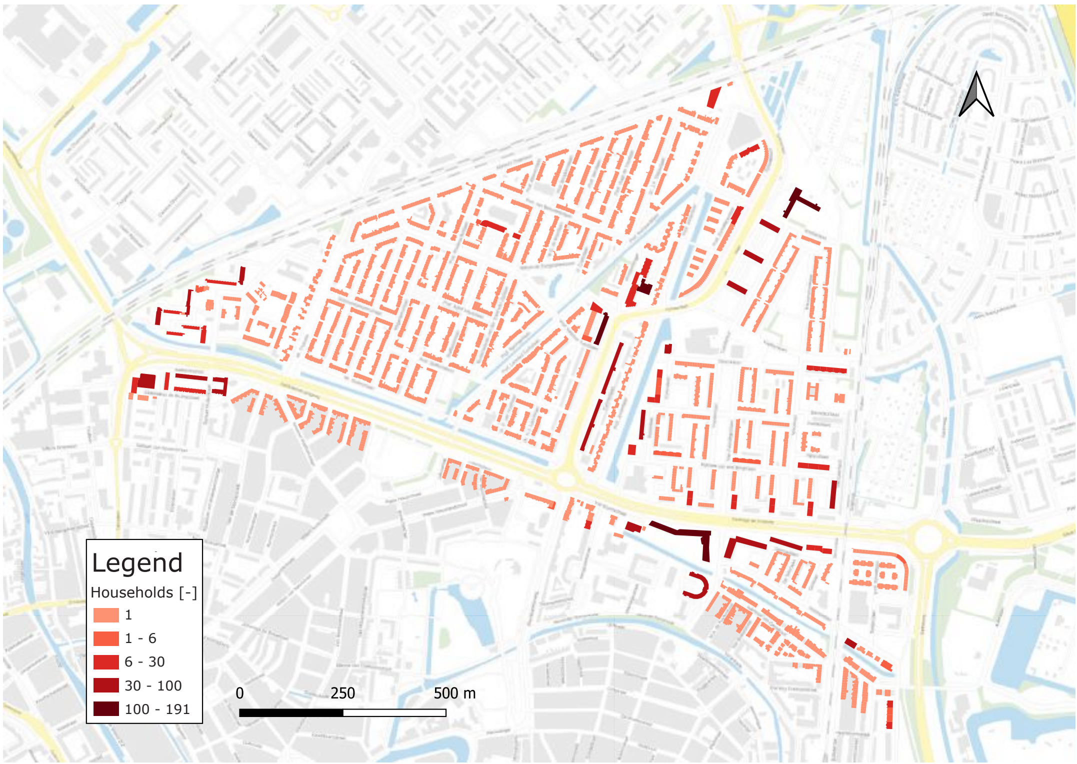


Figure 3.13: Number of households per building in Tuindorp

3.3.4. Costs of conduit reconstruction

The costs of repairing conduits are likely to be higher than the costs of performing maintenance and rehabilitation. This is due to, among others, the urgency of repairing. Within this section, the methods to determine costs for the repair and return to service are discussed. This is done for two failure mechanisms: structural sewer failure and water distribution network failure.

Sewer system

To estimate the renewal and maintenance costs for all sewer conduits in the study area, index numbers of Rioned are used (Stichting Rioned, 2015). According to Willemsen (personal communication, 4th April 2020), an urgency factor of 5% can be applied, for rescheduling and faster preparation of the repair works. In the event of structural sewer failure, conduit segments should be replaced. Costs of renewal can be divided into four categories:

1. Conduit
2. Earthwork (excavation and reinforcement)
3. Road surfacing (pavement removal and renewal)
4. Others

For the indication of pricing, a distinction can be made between plain concrete conduits (<700mm) and reinforced concrete pipes (>700mm). Conduits with a diameter smaller than 700mm have relatively low material costs, whereas conduits with larger diameters can be more expensive. The second category is earthwork, where the soil type and amount of replaced volume are of influence. As soil type is anthropogenic, this will not lead to mutual differences within the catchment area. The amount of soil replaced depends on, among others, the excavation slope, which is determined to be 0.75: 1. Other factors that influence the excavated volume are conduit diameter and depth and are variable per conduit section. Road surfacing is the third cost category, which accounts for 30% to 60% of the total renewal costs. For road surfacing a distinction can be made between pavement and asphalt. Reconstruction of asphalt road leads to higher costs compared to pavement. Differences in costs can amount up to €930/m for a conduit with a diameter of 700mm. Besides, the final category 'other' includes traffic measures, tree removal and accessibility of buildings. Additional costs, such as stamping and drainage, are not taken into account in this research. For these cost categories, a surcharge factor of 0.417 is applied, as well as the urgency factor of 5%, to calculate the total costs of renewal per metre. Examples of the calculation for reconstruction costs can be found in Appendix G.

The total costs of repairing can be calculated as the conduit costs per metre multiplied by the removal length. The total length of removal is assumed to be equal to the segment length, or a maximum length of 10m. Minimum costs of replacement are considered to be €250.

Water distribution network

Pipe failure in the water distribution network can be estimated using index numbers from water companies. According to Jacobs (personal communication, 19th March 2020), costs of renewal of pipe segments are around 1.5 times the diameter of the conduit (in mm). This includes costs of conduit, earthwork and road surfacing. For example, the replacement of a pipe with a diameter of 500mm will cost around €750 per metre. In the Tuindorp catchment, diameter ranges from 21 up to 710mm. Like sewer renewal, costs can be case-specific and can be different under local circumstances. However, additional costs for replacement are not taken into account in this research. To determine the total cost per pipe segment, renewal costs per metre are multiplied by the length of the conduit, with a maximum replacement length of 10m. Additionally, minimal replacement costs are assumed to be €250.

3.3.5. Drinking water supply outage

Failure in one of the conduits within the water distribution network leads to the outflow of drinking water and under pressure in the system, which affects the supply to households and business users. In this research, the impact of supply outage is calculated using the duration of supply outage or so-called 'Ondermaatse Leveringsminuten' (OLM). Failure of water distribution conduits leads to a supply outage of 180min (Jacobs, personal communication, 3rd February 2020). The duration of supply outage is assumed to be equal for all sections. It is derived from the sum of 30min until the notification, 30min to interrupt the water supply and 120min of repair.

To prevent the effects of individual events from spreading throughout the system, valves are placed. Figure 3.14 shows the location of the 542 valves in the Tuindorp catchment. Logically, more valves lead to a safer network and less damage in case of failure in the water distribution network (Liu et al., 2017). In this analysis, water supply outage is calculated when valves are closed. Pipe segments within the boundaries of valves are linked to estimate the number of customers that do not have access to the water supply in case of failure. Households that are located outside the boundaries of valves and experience low water pressure before closing of the valves are not taken into account.

A differentiation between residential and non-residential (school, commercial, public) building use is made, as patterns of water usage are different. More specifically, residential usage shows peak flows in morning and evening hours, while non-residential use shows peaks during mid-day (KWR, 2020). Subsequently, the number of affected costumers can be estimated by the number of residential and non-residential addresses in between the boundaries of the closed valves. As the OLM uses the average amount of supply outage, the number of affected customers is divided by the total number of addresses in Tuindorp. To calculate the OLM, this number is multiplied by the duration of supply outage, namely 180min. In formula, the total damage per conduit segment induced by water supply outage becomes:

$$\mathrm{OLM}_i = 180 \cdot \frac{\text{affected addresses}}{\text{total addresses}} \tag{3.8}$$

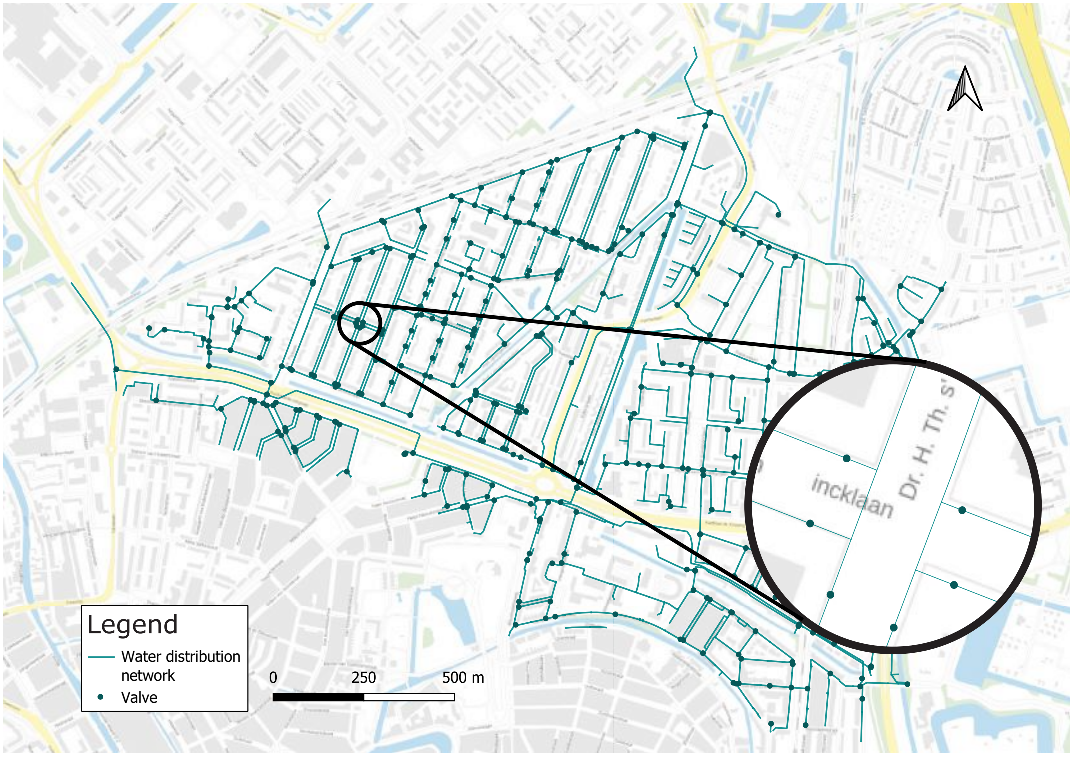
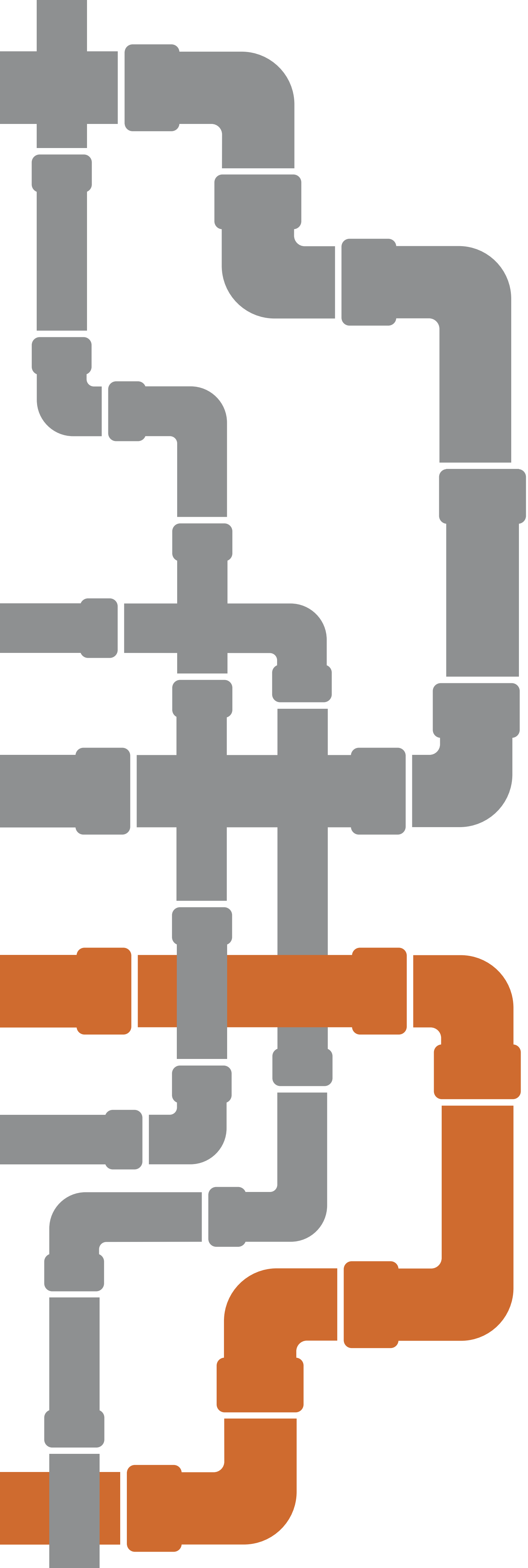


Figure 3.14: Locations of valves in Tuindorp



4

Results

In this chapter, the results are presented. The described methodologies are applied for the case study in Tuindorp, Utrecht. The first step was to determine the affected area of which results are presented in Appendix H. Results of the individual consequences are presented in the subsequent sections (4.1 - 4.5). Where possible, results of the sensitivity analyses are given. Finally, in Section 4.6, a comparison is made between the outcomes of the hydraulic network functioning (Section 3.1) and the consequences, in order to answer the third research question: 'What is the effect of the individual consequences of failure on the conduit criticality in underground water infrastructure?'

4.1. Damage to buildings

The amount of damage per conduit depends on the impact area caused by flooding and sinkhole formation in combination with the presence of buildings in the surrounded area. For the three types of failure mechanisms, damage to buildings is determined. Besides, the results of the sensitivity analysis are given.

4.1.1. Sewer system - structural failure

Structural sewer failure causes shearing of the soil above the conduit, leading to sinkhole formation, which can cause damage to the surrounding buildings. The total and the average number of buildings damaged per building category is presented in Table 4.1. In Tuindorp, 37 buildings are damaged if the whole sewer system would collapse, or 1.4 damages per hectare buildings. The maximum amount of buildings damaged by one conduit is 2.4, with an average of 0.05 affected buildings per segment. In case of failure, 92% of the conduits do not lead to damages. Besides, buildings of the categories 'high-risk objects', 'public' and 'education' are not affected in case of failure. The category with the most damages per hectare is 'housing', with an average of 0.04 hits per conduit, leading to a total of 31.9 damages in case of total system collapse.

Figure 4.1 presents the spatial distribution of the damages. It is found that conduits that lead to damage in case of failure are often located closer to buildings than conduits without damage. The conduit that causes the most damage is located at 10cm from housing, while the average distance is about 10m. Furthermore, there is no clear pattern in the amount of damage and the location of failure within the study area.

Table 4.1: Damage to the buildings categories in case of structural sewer failure

Category	**Total sum of damages**	**Average damage per conduit**	**Damages per area [hits/ha]**
Commercial	2.88	0.004	2.33
Housing	31.93	0.04	3.19
Other	2.42	0.003	0.77
Public	0	0	0
High-risk objects	0	0	0
Education	0	0	0
All	*37.2*	*0.05*	*1.38*

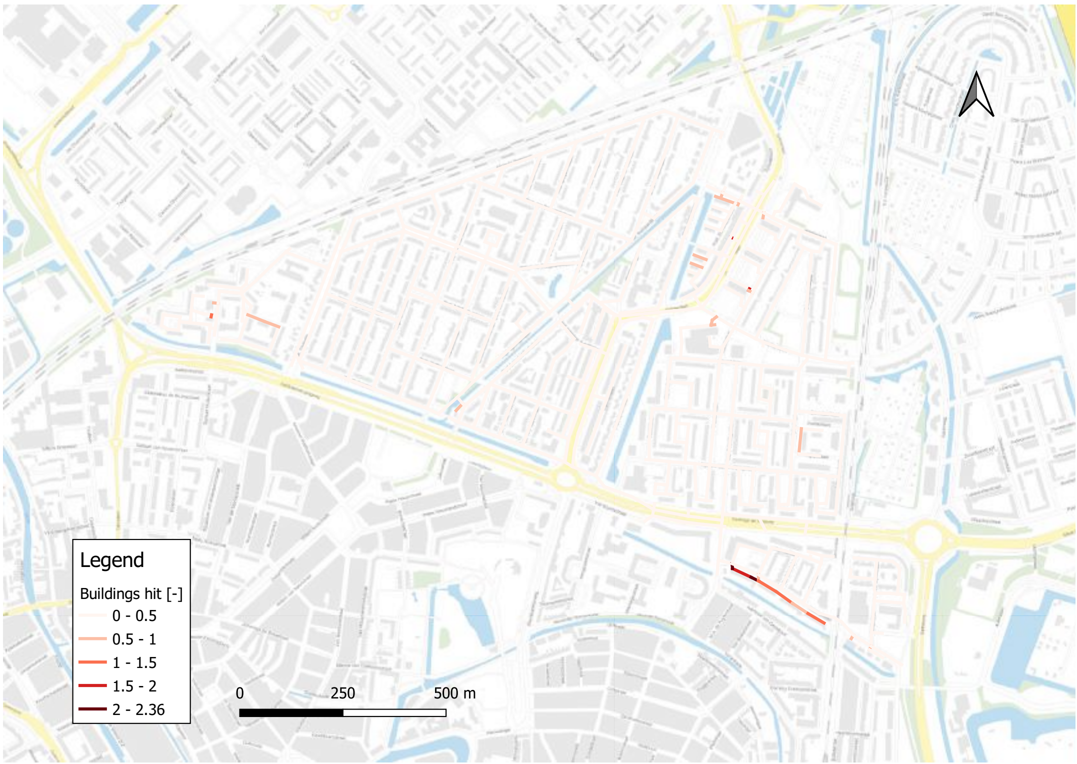


Figure 4.1: Total number of buildings hit in case of structural sewer failure

Sensitivity analysis

Results of the sensitivity analysis are presented in Table 4.2. The angle of repose is 30° in case of structural failure, as explained in Section 3.2.2. The radius of the sinkhole doubles in size when the angle of repose is decreased to 15°. When the angle of repose increases to 45°, the radius is halved compared to the initial sinkhole size. The correlation factor (τ_b, see Section 3.1) explains the linear relationship between the normalised results of the original sinkhole size with the results obtained with a 15° and 45° angle of repose.

It is found that the angle of repose is highly sensitive for the damage to buildings. The correlation between the results of the original sinkhole and the sinkhole with an angle of repose of 15° is 0.366. The number of buildings hit in case of total system collapse would become 444.5, which is a factor 12 higher as the original water damage. When the angle of repose increases to 45°, the sinkhole size is halved compared to the initial sinkhole size. Total damage to buildings becomes 7.7, which is a factor 5 smaller than the original value. For an angle of repose of 45° the correlation becomes 0.657. This indicates that there is a positive relationship between the outcomes of damage to buildings.

Table 4.2: Sensitivity analysis on the angle of repose for sinkhole formation in case of structural sewer failure

Angle of repose	Total damage to buildings	Correlation (τ_b)
15°	444.5	0.366
30° (base)	37.2	-
45°	7.7	0.657

4.1.2. Sewer system - hydraulic failure

In the case of hydraulic sewer failure, manhole flooding can occur. The location of flooding may be different than the location of the conduit, see Section 3.2.1. Failure of one conduit can lead to flooding at up to 259 manholes. However, not all conduits lead to flooding when they are blocked, as the system may function properly. Water may flow along other routes towards the WWTP, without causing flooding of the area. 78% of the conduit segments did not lead to buildings damaged in case of hydraulic failure. Table 4.3 shows the damages per building category. The highest number of buildings affected by one conduit is 76. On average, one conduit causes damage to 3.2 buildings. Buildings of the category 'other' are damaged most often, with averages of 1.77 damages per conduit failure or 435 damages per hectare. Per hectare, buildings categorised as 'other' are affected 8 times more often as 'commercial', 'housing' and 'public'. Furthermore, no high-risk objects and education buildings are affected by a hydraulic failure in the sewer network in the study area.

Table 4.3: Damage to the buildings categories in case of hydraulic sewer failure

Category	Total sum of damages	Average damage per conduit	Damages per area [hits/ha]
Commercial	67	0.09	54.26
Housing	1034	1.33	51.81
Other	1372	1.77	434.62
Public	27	0.03	52.11
High-risk objects	0	0	0
Education	0	0	0
All	*2500*	*3.22*	*92.84*

Figure 4.2 shows the total damage per conduit. The conduit that causes most water damage is located in the middle of the catchment. Furthermore, it is found that conduits that lead to damage are located around weirs. At these locations, CSO takes place in case of heavy precipitation events.

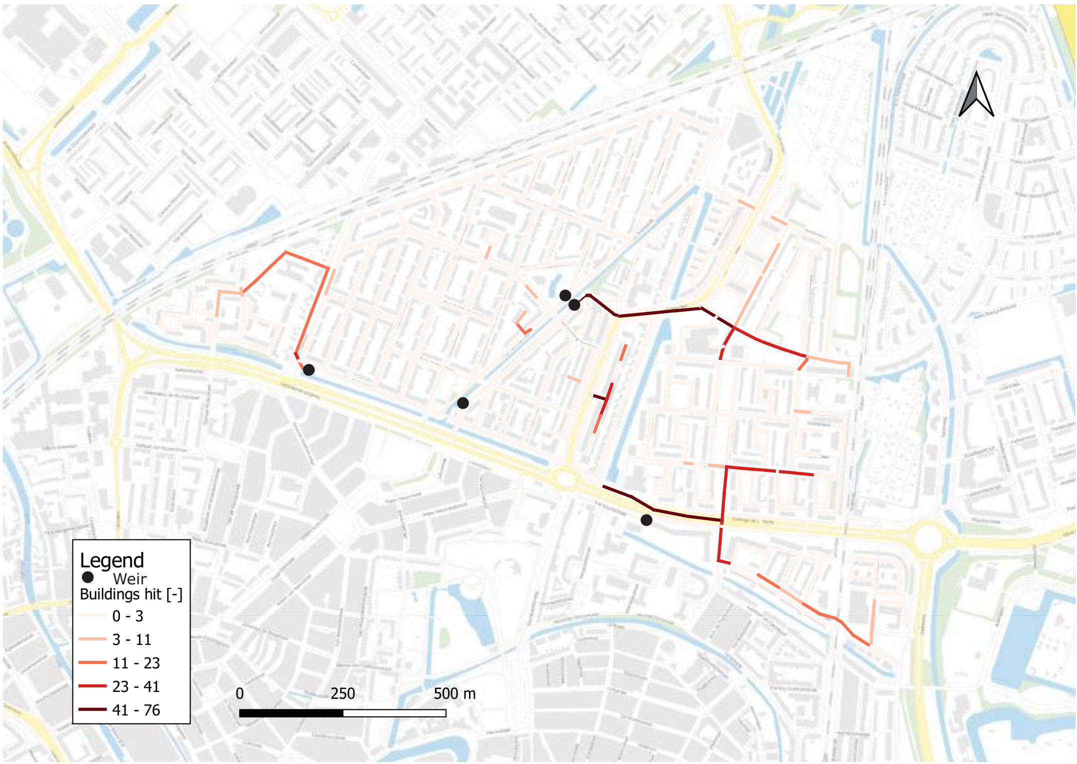


Figure 4.2: Total number of buildings hit in case of hydraulic sewer failure

Sensitivity analysis

It is found that water levels are below 20cm in case of manhole flooding with a 15m^3 flood volume, see Figure 4.3a and Figure H.2 in Appendix H. The water flow follows the road section and often stays between the boundaries of the sidewalks. A sensitivity analysis is performed to investigate water flows with variable flood volumes. Flood volumes of 7.5, 30 and 150m^3 are tested for several manholes in Tuindorp. Figure 4.3b provides an example of the flood zone with an increased flood volume of 150m^3. In this study area, the flooded area increases almost linearly with an increasing flood volume, where the water flows to the lowest point in the area. Conversely, when the volume of flooding changes, the maximum water depth remains approximately the same (<0.2m). This indicates that water often remains within the boundaries of the sidewalks. Hence, in flat study areas, it is expected that an increasing flood volume will not lead to a significant increase in water damage.

(a) Flood depth for a manhole in the catchment area, with a flood volume of 15m^3

(b) Flood zone for variable flood volume

Figure 4.3: Manhole flooding in Tuindorp

4.1.3. Water distribution network

In the case of water distribution network failure, the total damage is determined by the combined amount of damage induced by flooding and average conduit damaged by sinkhole formation. Damage to the different building categories caused by the flooded area and sinkhole formation are shown in Tables 4.4 and 4.5. Besides, the combined damage per category is shown in Table 4.6. The combined results imply that conduits with damages caused by the flooded area, do not necessarily lead to damages caused by sinkhole formation and vice versa. On average, 1.8 buildings are damaged per conduit in the event of failure. However, 30% of the conduits do not lead to damage in case of failure. The total amount of damage per hectare is 80 buildings. Relatively, buildings categorised as 'other' are damaged most, followed by 'housing' and 'high-risk objects'. Besides, damages to the category 'other' mainly occur by the exposure of flooding, with 109 damages per hectare.

Table 4.4: Damage to the buildings categories caused by the flooded area in case of water distribution network failure

Category	**Total sum of damages**	**Average damage per conduit**	**Damage per area [hits/ha]**
Commercial	44	0.02	25.82
Housing	1060	0.6	32.55
Other	454	0.26	108.96
Public	0	0	0
High-risk objects	3	0	67.42
Education	5	0	2.27
All	*1566*	*0.89*	*39.75*

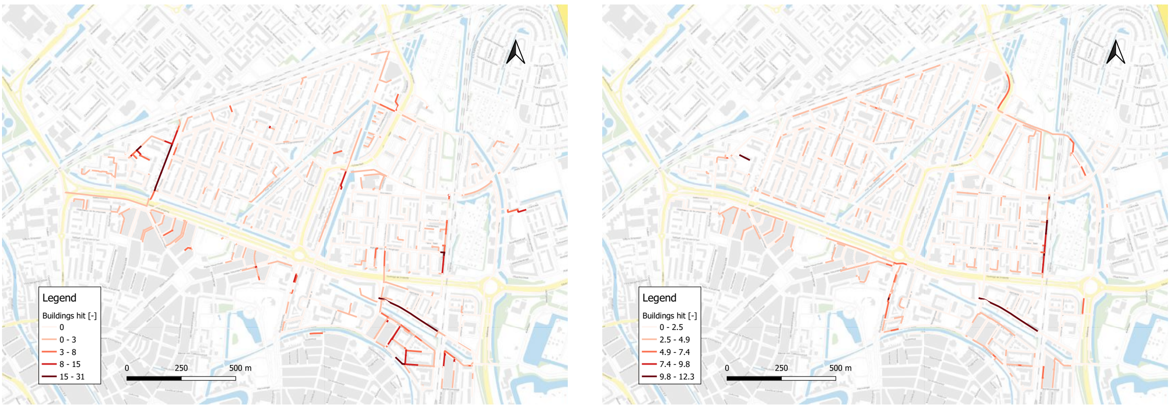
Table 4.5: Damage to the buildings categories caused by sinkhole formation in case of water distribution network failure

Category	**Total sum of damages**	**Average damage per conduit**	**Damage per area [hits/ha]**
Commercial	49.36	0.03	28.96
Housing	1921.99	1.08	62.31
Other	260.42	0.14	66.61
Public	2.93	0	4.2
High-risk objects	0.86	0	19.43
Education	13.77	0.01	6.26
All	*2234.3*	*1.26*	*56.71*

Table 4.6: Total damage to the buildings categories in case of water distribution network failure

Category	**Total sum of damages**	**Average damage per conduit**	**Damage per area [hits/ha]**
Commercial	74.91	0.04	43.95
Housing	2511.68	1.42	81.43
Other	525.01	0.30	134.29
Public	2.93	0	3.13
High-risk objects	3.57	0	80.35
Education	16.39	0.01	7.45
All	*3133.75*	*1.77*	*79.54*

Spatial results of the damages to buildings caused by sinkhole formation and flooding in case of water distribution network failure are shown in Figures 4.4a and 4.4b. The maximum amount of buildings damaged by sinkhole formation is 12.3, while for the flooded area this number is 31, both located in the south-eastern part of the catchment. This conduit section is located close to buildings, namely at 1m compared to 6m on average. The total combined damage caused by water distribution network failure is presented in Figure 4.4. There is no clear pattern visible on the number of damages within the catchment area.



(a) Damage to buildings caused by flooded area (b) Damage to buildings caused by sinkhole formation

Figure 4.4: Spatial distribution of buildings hit caused by flooding and sinkhole formation in case of water distribution network failure in Tuindorp

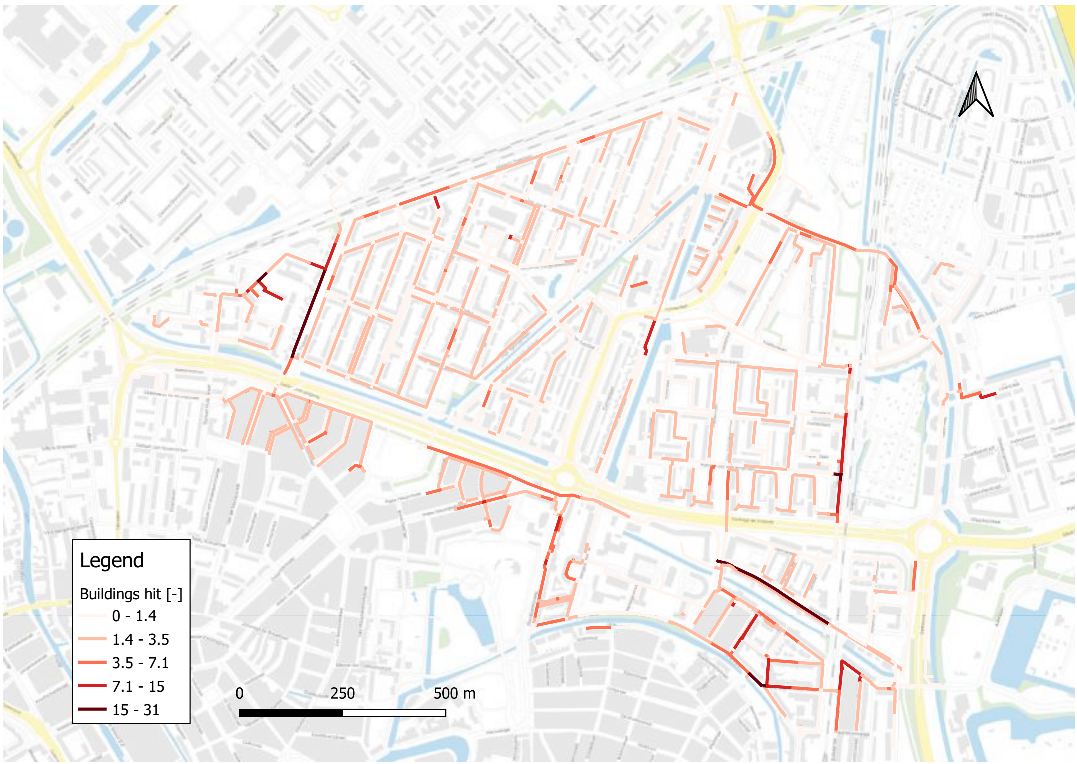


Figure 4.5: Total number of buildings hit in case of water distribution network failure in Tuindorp

Sensitivity analysis

A sensitivity analysis is done on the sinkhole area, as it is stated that the sinkhole size may be up to four times the real size of the sinkhole (see Section 3.2.2). Therefore, the sinkhole size is decreased to 1/2 and 1/4 of the original sinkhole size. Results of the sensitivity analysis are shown in Table 4.7. The correlation between the results is positive. However, the correlation coefficient decreases to 0.22, when the sinkhole area becomes 1/4th of the original sinkhole size. The total amount of damages decreases to 543 and 42, for sinkhole formation only. This indicates that there is an exponential relationship between the amount of damage and sinkhole size. A smaller sinkhole size leads to significantly less damage. Hence, the sinkhole size is sensitive to the outcomes of water damage.

Table 4.7: Sensitivity analysis on variable sinkhole size for damage to buildings in case of water distribution network failure

Sinkhole area	**Total damage to buildings by sinkhole formation**	**Correlation (τ_b)**
1 (base)	2234	-
$0.5 \cdot$ base	543	0.427
$0.25 \cdot$ base	42	0.221

4.2. Traffic obstruction

Traffic obstruction is characterised by slower velocities, longer trip times and increased vehicular queuing. In the case of failure in an underground water network, obstacles on the road cause a blockage. Different methods to determine the traffic obstruction are presented in Section 3.3.2. The total number of road types that can be damaged is six: bicycle path, local road, main road (one or two directions), sidewalk, parking space and railway. The results of the traffic obstruction for the sewer system and water distribution network failure are described below. Moreover, a sensitivity analysis is performed.

4.2.1. Sewer system - structural failure

Results of the traffic obstruction analysis for structural sewer failure are presented in Table 4.8. On average, 2.55 road types are damaged when one conduit fails. Almost every conduit failure leads to obstruction of a local road (86%), sidewalk (94%) or both (84%). The total amount of combinations of failures is 31, with a maximum number of five road types obstructed by one conduit. In total, 23% of the failures lead to a damaged main road, either one direction or both directions. In 123 cases (16%) are both directions blocked, while in 56 cases (7%), there is only one direction of flow obstructed. When the obstruction per hectare is observed, parking spaces are obstructed most (43/hectare), followed by local road (29/hectare) and bicycle path (25/hectare).

Table 4.8: Damage to the different road categories in case of structural sewer failure

Category	**Total sum of damages**	**Average damage per conduit**	**Obstruction per area [hits/ha]**
Bicycle path	121	0.16	25.22
Local road	671	0.86	29.75
Main road - *both directions*	123	0.16	8.26
Main road - *one direction*	56	0.07	3.76
Sidewalk	735	0.95	13.39
Parking space	276	0.36	42.61
Railway	1	0	0.2
All	*1983*	*2.55*	*18.25*

Figure 4.6 shows the normalised number of road impact over the catchment area. A clear pattern of critical conduits and main roads is visible. At locations where conduits hit the main road, in over 50% of the cases a bicycle path and local road are hit as well. As sewer lines are not located close or under the railway system, this road type is only damaged once, in the south-east.

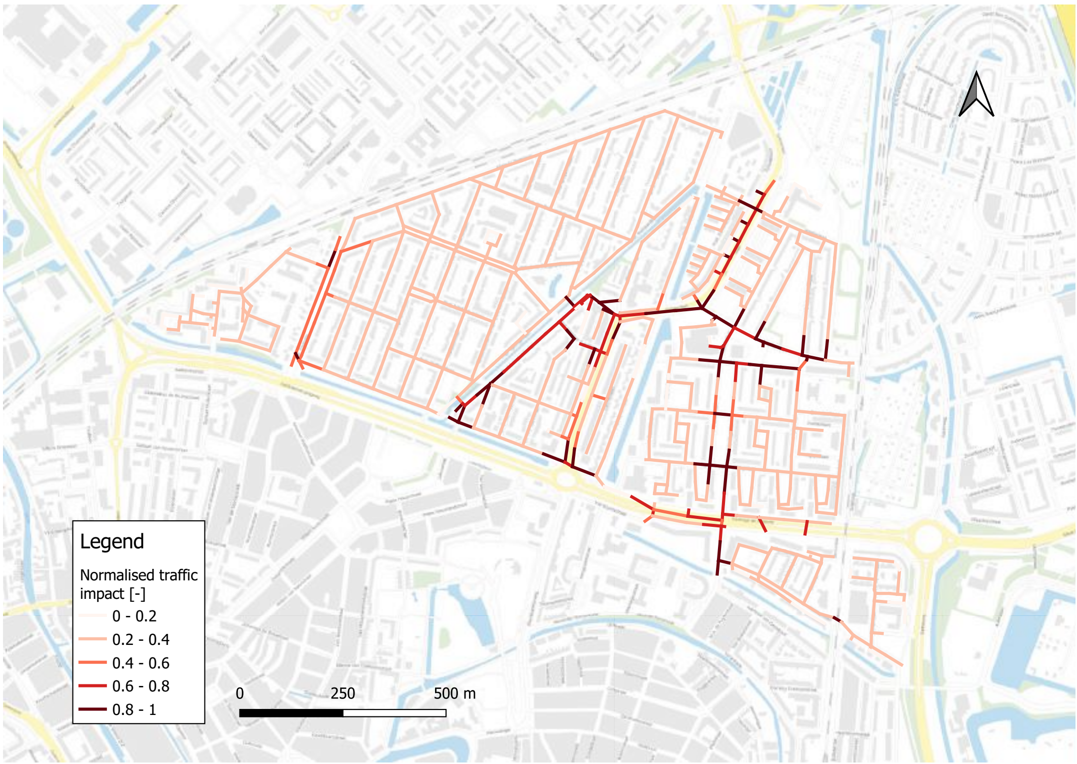


Figure 4.6: Normalised traffic impact from 0 (least critical) to 1 (most critical) by structural sewer failure

Sensitivity analysis

A sensitivity analysis is done on the angle of repose for the sinkhole formation. Table 4.9 shows the outcomes of the average obstruction per conduit and correlation factors. For an angle of repose of 15° the sinkhole radius doubles in size, while a 45° angle leads to a sinkhole half of the original radius (see Figure 3.10). With an angle of 15°, the average obstruction is 2.79, which indicates an increase in damages of 9% compared to the base sinkhole. On the other hand, a 45° angle causes damages to 2.16 road categories or a decrease of 18%. Furthermore, the correlation factors (τ_b) between the outcomes show a positive relation (0.818 and 0.75). Largest differences in outcomes can be deduced from results in the categories 'sidewalk' and 'parking space'. The category sidewalk is hit by 99% and 70% of the conduits respectively for a 15° and 45° angle. For the parking spaces, these numbers are 46% and 27%.

Table 4.9: Sensitivity analysis on the angle of repose for traffic obstruction in case of structural sewer failure

Angle of repose	Average traffic impact	Correlation (τ_b)
15°	2.79	0.818
30° (base)	2.55	-
45°	2.16	0.75

4.2.2. Sewer system - hydraulic failure

The total sum of damages and average damage caused by one water distribution conduit failure are presented in Table 4.12. The average number of road types damaged by one conduit in case of failure is 2.8. The total number of failure combinations is 38, for example, a bicycle path and railway. As water distribution conduits are often located under sidewalks in the Netherlands, 98% of the conduits cause damage to a sidewalk in case of failure. In 86% a local road is damaged. Third most damaged infrastructure type is 'parking space', with damages in 47% of the failure cases. However, per hectare, parking spaces (129) and bicycle paths (82) are obstructed most. The combination of obstruction of a sidewalk, parking space and local road occurs most often, respectively 208 times, or 37% of all failure combinations. As bicycle paths and main roads are not present within the whole catchment, respectively 22% and 27% of the conduits causes damage to these road types. In Tuindorp, 70% of main roads obstructions are in both directions, while 30% is only in one direction. Regarding railway infrastructure, 1% of the conduits causes damages to the railway, at the locations where water lines cross the railway network.

Figure 4.7 shows the spatial distribution of damages per conduit. The maximum number of road types blocked, induced by one conduit, is three. Conduits located in the south-western part are found most critical due to damages to main roads. Besides, locations with road obstruction are found in the middle and eastern part of the catchment, around locations of weirs.

Table 4.10: Damage to the road categories in case of hydraulic sewer failure

Category	**Total sum of damages**	**Average damage per conduit**	**Obstruction per area [hits/ha]**
Bicycle path	20	0.03	4.17
Local road	0	0	0
Main road - *both directions*	7	0.01	0.47
Main road - *one direction*	0	0	0
Sidewalk	220	0.28	4.01
Parking space	94	0.12	14.51
Railway	0	0	0
All	*341*	*0.44*	*3.14*

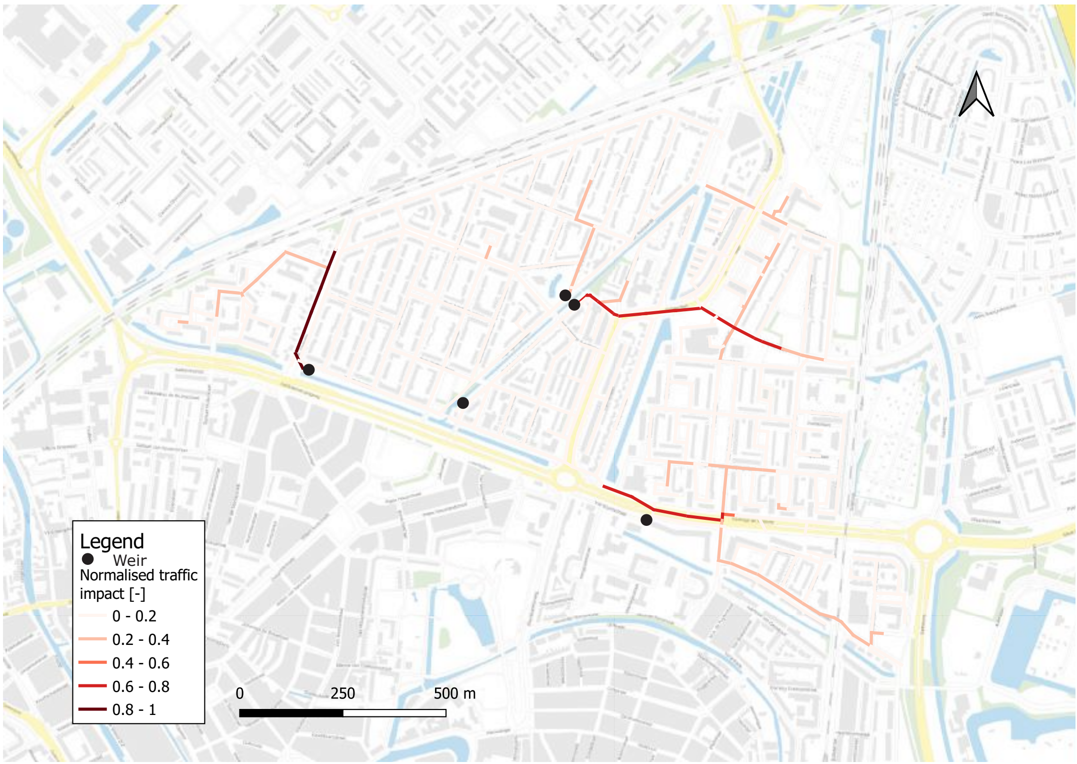


Figure 4.7: Normalised traffic impact from 0 (least critical) to 1 (most critical) by hydraulic sewer failure

Sensitivity analysis

Per category, a low and high threshold level is used to determine the robustness of the results. Lower boundary values indicate that the specific road type is no longer accessible with a lower water depth compared to base values. A higher threshold leads to road blockage at higher water depths. Table 4.11 shows the results of the average traffic impact and correlation factors. On average, the number of roads obstructed by one conduit is 0.84 and 0.13 for low and high thresholds, compared to 0.44 for the base threshold. The correlation between the outcomes is 0.617 and 0.663, which indicates a positive relationship between the outcomes. With a lower threshold, the possible number of failure combinations becomes 21, compared to 7 possible combinations in the base model. For the higher thresholds, this number is 2: only blockage of sidewalks or no road obstructions. For the category sidewalk, a lower threshold value results in 4% more blockages, while a higher threshold leads to 54% fewer obstructions. For local roads and railways, the lower threshold leads to blockage of 121 and 10 roads, while the base and higher boundary values do not lead to blockages.

Table 4.11: Sensitivity analysis on variable thresholds for traffic obstruction in case of hydraulic sewer failure

Threshold	**Average traffic impact**	**Correlation (τ_b)**
lower value	0.84	0.617
base	0.44	-
higher value	0.13	0.663

4.2.3. Water distribution network

The total sum of damages and average damage caused by one water distribution conduit failure are presented in Table 4.12. The average number of road types damaged by one conduit in case of failure is 2.8. The total number of failure combinations is 38, for example a bicycle path and railway. As water distribution conduits are often located under sidewalks in the Netherlands, 98% of the conduits cause damage to a sidewalk in case of failure. In 86% a local road is damaged. Third most damaged infrastructure type is ‘parking space’, with damages in 47% of the failure cases. However, per hectare, parking spaces (129) and bicycle paths (82) are obstructed most. The combination of obstruction of a sidewalk, parking space and local road occurs most often, respectively 208 times, or 37% of all failure combinations. As bicycle paths and main roads are not present within the whole catchment, respectively 22% and 27% of the conduits causes damage to these road types. In Tuindorp, 70% of main roads obstructions are in both directions, while 30% is only in one direction. Regarding railway infrastructure, 1% of the conduits causes damages to the railway, at the locations where water lines cross the railway network.

Table 4.12: Damage to the different road categories in case of water distribution network failure

Category	**Total sum of damages**	**Average damage per conduit**	**Obstruction per area [hits/ha]**
Bicycle path	391	0.22	81.5
Local road	1516	0.86	67.21
Main road - *both directions*	338	0.19	22.71
Main road - *one direction*	135	0.08	9.07
Sidewalk	1740	0.98	31.71
Parking space	837	0.47	129.22
Railway	15	0.01	2.97
All	*4972*	*2.81*	*45.77*

Results of the number of damages per conduit over the study area are shown in Figure 4.8. On average, conduits with large diameters obstruct more road categories and are often located near or under main roads. Within the neighbourhood, it appears that the eastern part is more critical for traffic obstruction.

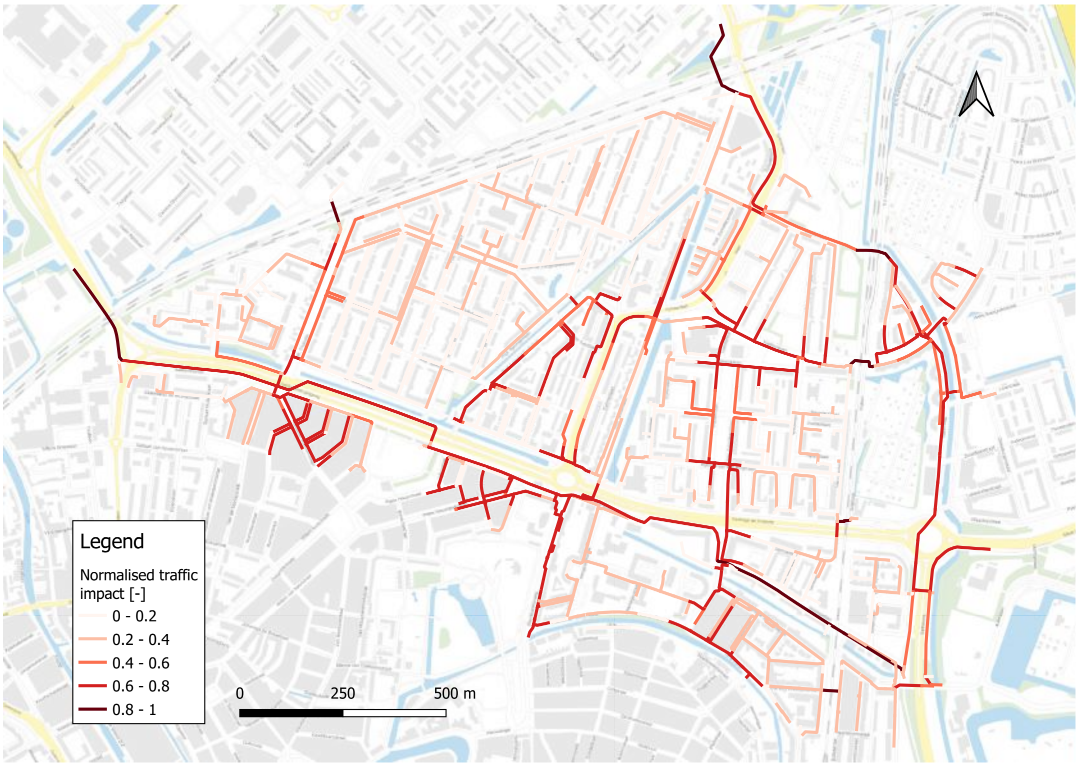


Figure 4.8: Normalised traffic impact from 0 (least critical) to 1 (most critical) by water distribution network failure

Sensitivity analysis

Damages induced with variable sinkhole sizes are tested. Again the sinkhole size is decreased to a half and a quarter of the original sinkhole area to see the differences. Table 4.13 shows the results of the analysis. Correlation factors between outcomes are 0.705 and 0.471. This indicates that there is a positive correlation between the results. The base model shows an average obstruction to 2.8 out of 6 road types. When the sinkhole size is decreased, the average damage of a conduit failure decreases to 2.47 and 2.17, or a decrease of 14% and 29%. The largest decrease in damages can be found in the number of parking spaces hit by a conduit, which decreases from 47% (original) to 33% and 26%.

Table 4.13: Sensitivity analysis on variable sinkhole size for traffic obstruction in case of water distribution network failure

Sinkhole area	Average traffic impact	Correlation (τ_b)
1 (base)	2.81	-
0.5 · base	2.47	0.705
0.25 · base	2.17	0.471

4.3. Impact on human health

Figure 4.9 shows the results of the impact on human health within the study area. The impact on human health is defined as the number of possible infections per hydraulic conduit failure. To estimate the number of people that get in contact with the water, a radius of 10m around the flooded area is applied. The maximum number of possible infections for one conduit is 319. From the results, it is found that the average amount of infections per conduit is 12. As sewers may function properly in case of hydraulic failure, not all the conduits lead to flooding. In fact, 531 out of the 777 conduits (68%) do not lead to flooding, and thus infections, in case of hydraulic failure in the Tuindorp sewer network.

The conduits that lead to the most infections are located in the centre of the catchment area. These conduits lead to flooding at multiple manholes in the eastern part of the catchment. Besides, flooding in the east part has a significant impact due to the high population density. Other places with high infection risks are located in the southern part. Here, multiple weirs are located, as well as apartment buildings with high population density. The high percentage of children in the western part of Tuindorp does, on average, not lead to higher infection risks.

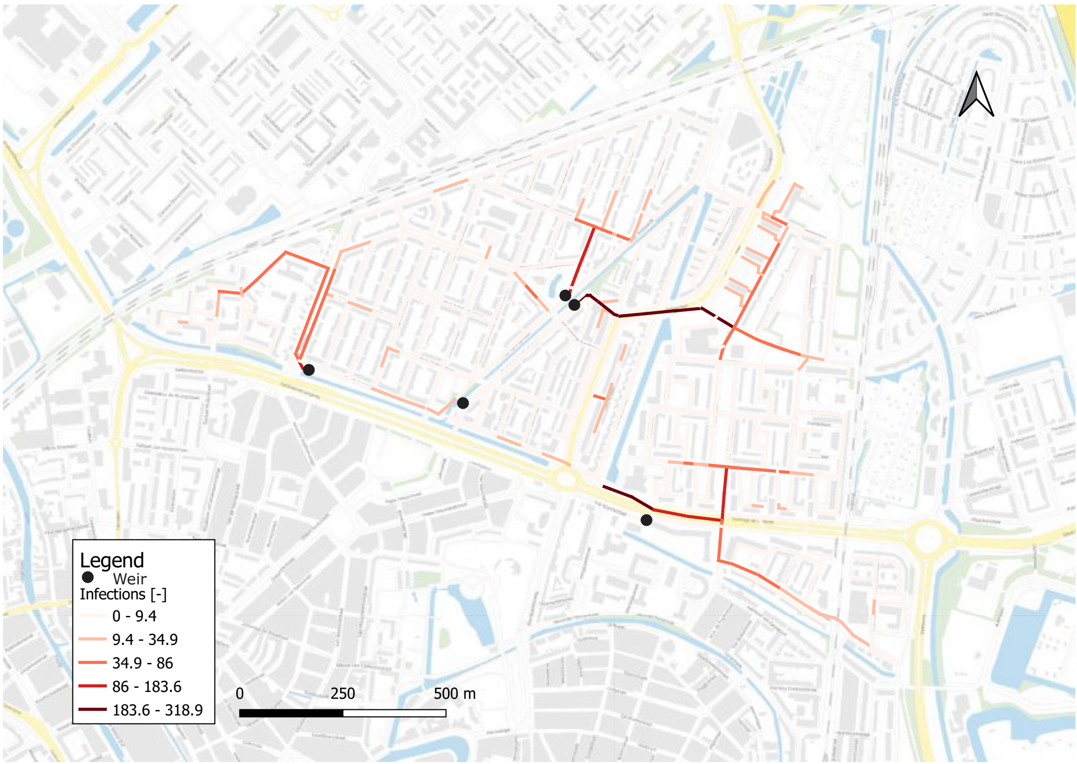


Figure 4.9: Impact on human health in case of hydraulic sewer failure

Sensitivity analysis

A sensitivity analysis is performed for 1) the radius of people that get in contact with the flooded area and; 2) the size of the flooded area. For the first analysis, round buffers with a radius of 10, 15 and 25m are taken into account. Here, the 10m radius is stated as the base. As the distance between buildings in different streets is more than 25, the round buffer only causes a 1% counting error for the health analysis. The average infection risk increases from 12.3 up to 13.3 and 15.9 for a 15 and 25m radius respectively (Table 4.14). The number of conduits without impact on human health stay equal with an increasing radius. The correlation between the outcomes is almost 100% linear, with correlation factors of 0.980 and 0.961. Therefore, results are not sensitive to the radius of impact.

Secondly, a sensitivity analysis on the flooded area is done, see Table 4.15. The flooded area is doubled and halved to test the sensitivity of the flood zone on the impact on human health. Subsequently, a radius of 10m around the flooded area is applied. The average infection risk with a flooded area half of the original size is 10.6 or 16% fewer infections. A flooded area doubled in size lead to an average of 12.7 infections or 3% more infections compared to the base model. Correlation factors of 0.968 and 0.99 imply that there is an almost perfect positive linear relationship between the outcomes.

Table 4.14: Sensitivity analysis on the radius in which people get in contact with the flood water for the impact on human health

Radius of impact	Average impact on human health	Correlation (τ_b)
10 (base)	12.30	-
15	13.25	0.980
25	15.86	0.961

Table 4.15: Sensitivity analysis on the flooded area for the impact on human health

Flooded area	Average impact on human health	Correlation (τ_b)
$0.5 \cdot$ base	10.61	0.968
1 (base)	12.30	-
$2 \cdot$ base	12.69	0.990

4.4. Costs of conduit reconstruction

In the case of conduit structural failure, reconstruction should take place. Costs regarding reconstruction include worker salaries, material costs and groundwork. For two failure mechanisms (structural sewer and water distribution network), results of the costs of conduit reconstruction are illustrated.

4.4.1. Sewer system - structural failure

Results of the reconstruction analysis are presented in Figure 4.10. Given a total system collapse, reconstruction costs add up to around €4,825,000. The costs for the reconstruction of pipe segments, with a maximum length of 10m, vary between €1,000 and €13,500, including the urgency factor of 5%. The costs are divided into four categories: conduit, earthwork, road surfacing and other. It is found that 66% of the costs consist of the reconstruction of road pavements. Average reconstruction costs per conduit failure are €6,700. This corresponds to a large pipe segment (>10m) with a diameter of 350mm and a depth of 2m, with an asphalt road.

Highest costs of conduit reconstruction can be found along the main roads. Conduits situated under main roads generally have large diameters and conduit depth; width between 800 and 900mm and a depth larger than 2.5m. Besides, over 90% of the road surfacing in Tuindorp is asphalt, resulting in higher costs for road surfacing compared to pavement.

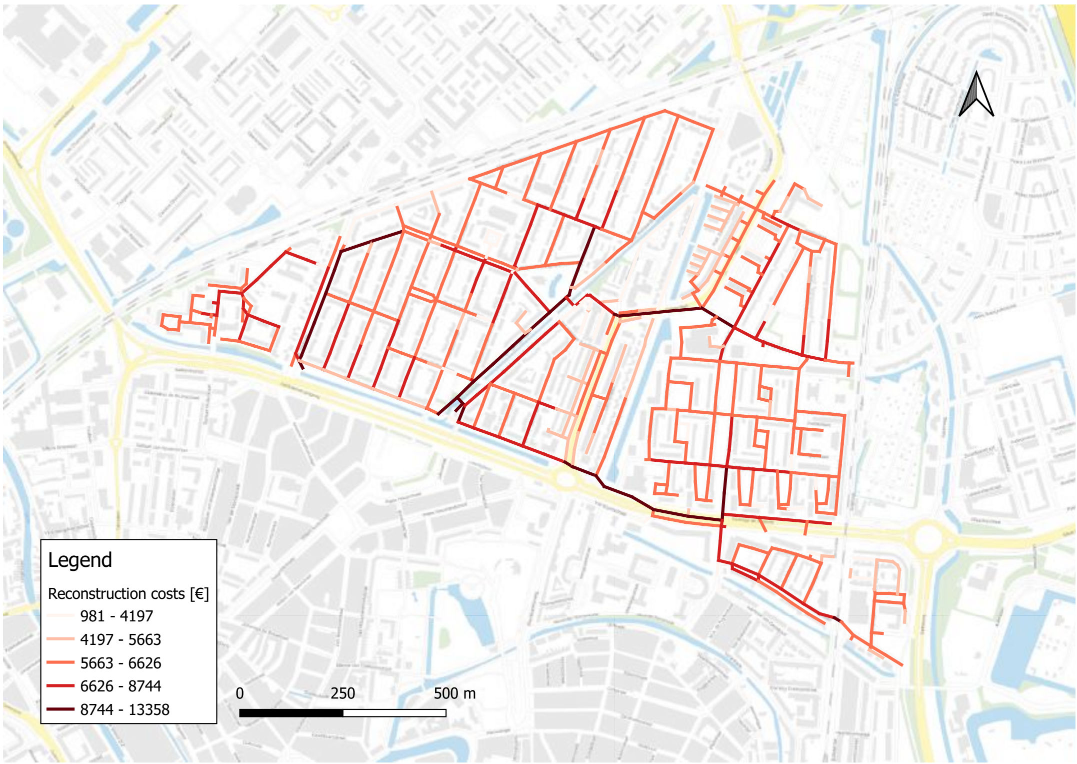


Figure 4.10: Costs of conduit reconstruction in case of structural sewer failure

4.4.2. Water distribution network

In the event of water distribution network failure, a segment with a maximum length of 10m is replaced. Figure 4.11 shows the results of the costs of reconstruction for water distribution conduits. The total costs of replacement in case of total system collapse are around €2,225,000 for all conduit segments within the study area. Reconstruction costs per water distribution pipe range between €250 and €10,500, with an average of €1,250.

The outcomes show a clear pattern of the network structure, as it is stated that costs are related to the diameter of the conduit. Conduit segments with large diameters (>400mm), and thus higher costs, are located at the borders of the catchment, except for the northwestern borders. Moreover, these conduits with high reconstruction costs are located along main roads of Tuindorp.

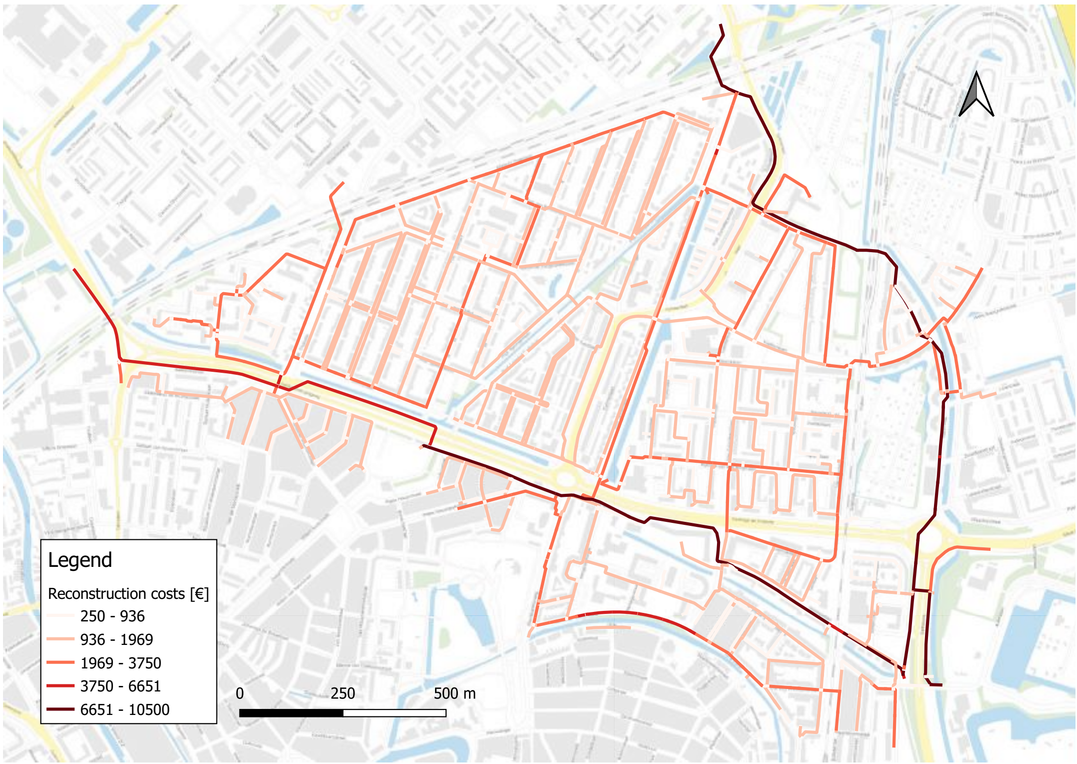


Figure 4.11: Costs of conduit reconstruction in case of water distribution network failure

4.5. Drinking water supply outage

The average time with substandard delivery of drinking water (OLM) is presented in Figure 4.12. The analysis is performed when valves are closed, only take into account households that do not have access to the water supply. Households that experience low water pressure are not taken into account. The figure represents the total time without water for both the residential and non-residential addresses. The OLM varies between 0min and 6min40s for one failure event. The average OLM is 52sec for one conduit failure.

The conduit segments with the highest OLM are located in the north and south, along the main roads. Here, crucial conduits are placed, as they are connected with multiple other lines within the system. However, when a sufficient number of valves are placed OLM can be minimised, as can be seen at the western end of the main road. On average, a larger drinking water supply outage is present at the eastern side of the study area. Here, a high number of addresses are connected to one pipe section, that is to say, more apartment buildings with a high population density. In the western part of the catchment area, the OLM is relatively small (<1min). Sufficient valves are placed and in case of failure, few households are affected.

Besides the total OLM, the differences between residential and nonresidential usage are observed. The distribution of residential and nonresidential OLM is respectively 99% and 1%. This is in line with the total percentage of residential and nonresidential addresses in the study area. It is found that locations with high nonresidential OLM have low residential OLM and vice versa.

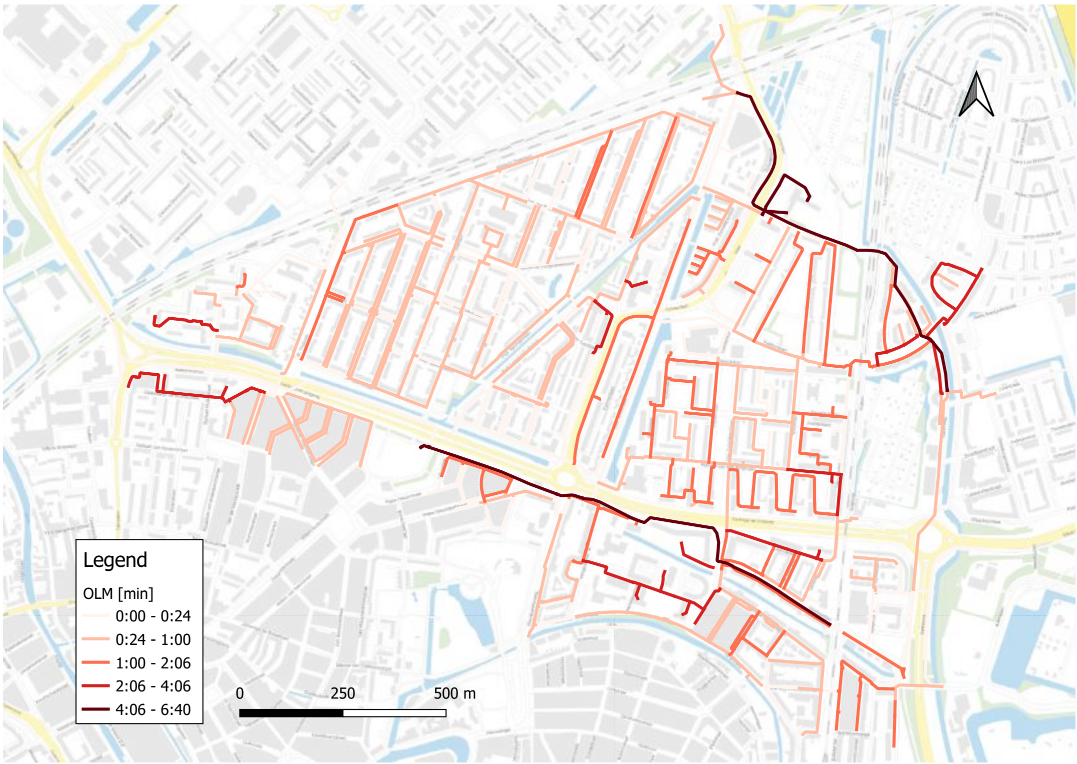


Figure 4.12: Duration of supply outage (OLM) in case of water distribution network failure

4.6. Overview of consequences

This section summarises the different consequences per failure mechanism: structural sewer, hydraulic sewer and water distribution network failure. The interrelationships between the consequences of failure are presented. Moreover, this section shows the correlation between the individual consequences and hydraulic functioning of the network types according to the GTM (Section 3.1). This is done in order to answer the third research question: 'What is the effect of the individual consequences of failure on the conduit criticality in underground water infrastructure?'

4.6.1. Sewer system - structural failure

Structural sewer failure leads to partial or complete loss of the load-carrying capacity, resulting in the formation of a sinkhole around the failure location. Structural failure of conduits leads to damage to buildings (Section 4.1.1), traffic obstruction (Section 4.2.1) and the reconstruction of sewer conduits (Section 4.4.1). Per individual consequence, the rate of criticality per conduit is calculated and normalised. Conduits with a criticality of 1 are identified as most critical and thus most important for the particular consequence. A criticality of 0 indicates that the conduit is the least critical.

Figure 4.13 shows the interrelation between different consequences of structural sewer failure. Besides, the figure presents the relation between individual consequences and hydraulic functioning according to the GTM. Results show that there is no correlation between the outcomes of the individual consequences. The correlation between 'damage to buildings' - 'traffic obstruction' and 'damage to buildings' - 'costs of conduit reconstruction' is -0.06. For damage to buildings, only a few elements are identified as being critical. The elements with a criticality larger than 0.5 for damages to buildings have a criticality around 0.4 for both costs of conduit reconstruction and traffic obstruction. Besides, the correlation between 'traffic obstruction' and 'costs of conduit reconstruction' is 0.13, illustrating that there is no relationship between the results.

The bottom column in Figure 4.13 shows the correlation factors between the hydraulic functioning of the sewer network (see Section 3.1) and the individual consequences of structural sewer failure. The outcomes of the scatter plots of the hydraulic network functioning with the consequences of failure are presented in the rightmost row. Results show that there is no correlation between the outcomes. The correlation (τ_b) between the hydraulic system functioning and 'damage to buildings' is 0.14, where conduits with a high criticality for hydraulic functioning may be indicated as critical for damage to buildings as well. However, also contradictory results are visible, where important conduits for analysis of damage to buildings are not critical for hydraulic functioning and vice versa. The correlation factor for ‘costs of conduit reconstruction’ and the hydraulic functioning is 0.05, indicating that there is no correlation between the outcomes. Nonetheless, it is found that conduits with a large diameter are critical for both reconstruction and system functioning, shown in the circle. Dead-end segments with small conduit diameters are only critical according to the hydraulic system functioning. Finally, the correlation between the hydraulic system functioning and ‘traffic obstruction’ is 0.10. This suggests that there is no correlation between the two outcomes.

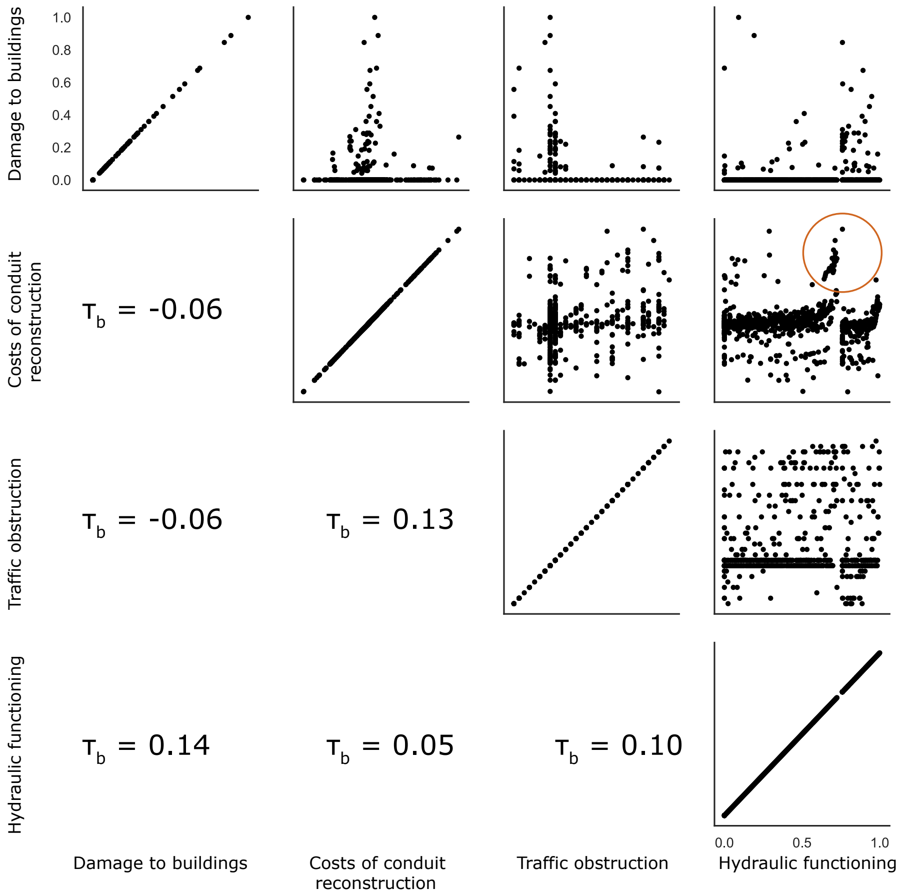


Figure 4.13: Overview of the correlation of conduit criticality based on the consequences of structural sewer failure and the hydraulic system functioning. Values within the circle indicate the positive relation between critical conduits with large diameters.

4.6.2. Sewer system - hydraulic failure

Hydraulic failure of sewer conduits occurs when a system does not meet serviceability requirements with respect to system performance, for example when a system is fully blocked. This results in the flooding of streets with consequences to the built environment. Consequences of hydraulic failure of sewer conduits are damage to buildings, impact on human health and traffic obstruction, of which results are presented in Sections 4.1.2, 4.2.2 and 4.3.

Figure 4.14 presents the outcomes of the scatter plots and correlation factors between the consequence analyses and hydraulic functioning according to the GTM. The Kendall rank correlation coefficient shows a positive relationship between the different consequence analyses. The correlation between the criticality of ‘traffic obstruction’ and ‘damage to buildings’ is 0.66, which implies that there is a positive relationship between the outcomes. The correlation coefficient between ‘damage to buildings’ and ‘impact on human health’ is 0.75, where most critical conduits show similarities. Conduits with a high amount of damages to buildings result in a high amount of health impact as well. Furthermore, the correlation between ‘traffic impact’ and ‘impact on human health’ is 0.84, indicating that there is a positive relationship between the results of both analyses.

The correlations between the hydraulic functioning and individual consequences of hydraulic sewer failure are shown in the bottom row and rightmost column of Figure 4.14. The Kendall rank correlation coefficient (τ_b) between the hydraulic functioning and 'damage to buildings' is 0.34, which indicates a slightly positive correlation between both outcomes. For the impact on human health, the correlation is 0.37. Both the results of 'damage to buildings' and 'impact on human health' with the hydraulic functioning show two peaks. This can be explained by the fact that conduits with large diameters are identified as critical, for both hydraulic functioning, 'damage to buildings' and the 'impact on human health'. While on the contrary, dead-end segments are only found critical for system functioning according to the GTM. Furthermore, hydraulic sewer conduit failure rarely leads to damage to buildings, resulting in multiple conduits classified as 'not critical' (0). Finally, the correlation (τ_b) between the hydraulic system functioning and traffic obstruction in case of hydraulic sewer failure is 0.39. This indicates that there is a positive relationship between the two outcomes. Conduits with a criticality larger than 0.5 for traffic obstruction, have a criticality larger than 0.5 for the hydraulic system functioning as well.

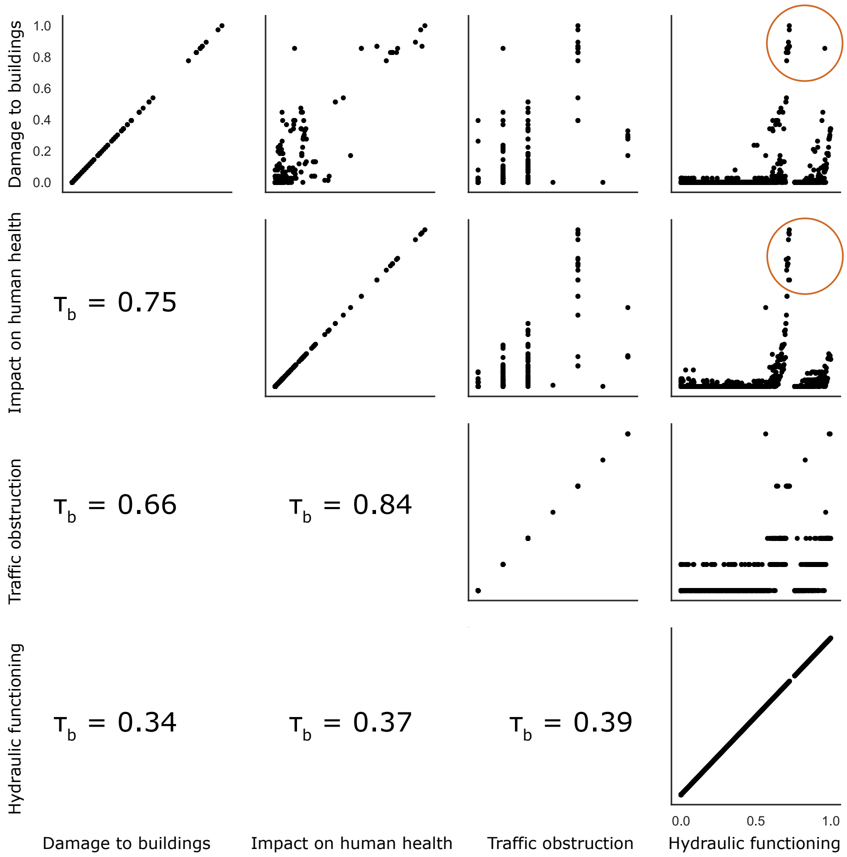


Figure 4.14: Overview of the correlation of conduit criticality based on the consequences of hydraulic sewer failure and the hydraulic system functioning. Values within the circles indicate the positive relation between critical conduits with large diameters.

4.6.3. Water distribution network

Failure of the water distribution network leads to the outflow of water resulting sinkhole formation and a flooded area. Four different consequences can be determined: damage to buildings (Section 4.1.3), traffic obstruction (Section 4.2.3), costs of conduit reconstruction (Section 4.4.2) and drinking water supply outage (Section 4.5).

The correlation between the results of the different consequences for water distribution network failure is presented in Figure 4.15. The correlation factor for 'damage to buildings' is 0.10 in combination with 'traffic obstruction', 0.12 with 'drinking water supply outage', and 0.24 with 'costs of conduit reconstruction'. Results show no correlation between the conduit criticality of buildings damaged and the other consequences of failure. Moreover, only 5% of the conduits for damage to buildings have a conduit criticality higher than 0.2. The correlations between 'costs of conduit reconstruction' - 'traffic obstruction' and 'costs of conduit reconstruction' - 'drinking water supply outage' are respectively 0.15 and 0.05, indicating that there is no relation.

Finally, 'traffic obstruction' and 'supply outage' suggest that there is no relationship, as the correlation factor is 0.07 and the scatter plot shows a wide spread of results.

Results of the hydraulic network functioning do not take into account conduits below the southern main road of Tuindorp. Therefore, only overlapping conduits are taken into account by determining the correlation between individual consequences and the system functioning according to the GTM.

The correlation factor (τ_b) between the hydraulic functioning with 'drinking water supply outage' and with the 'traffic obstruction' is respectively -0.06 and 0.09. This suggests that there is no relationship. When the spatial results are compared (Figures 3.4, 4.12 and 4.8), conduits identified as critical are located along main roads, for both the hydraulic functioning, drinking water supply outage and traffic impact. However, according to the hydraulic network functioning, other critical elements are located in the western part of the catchment. On the contradictory, for traffic obstruction and drinking water supply outage, these elements are located on the eastern side of the catchment. The correlation value between system functioning and costs of conduit reconstruction in case of water distribution network failure is 0.19. For the analysis of reconstruction costs, 92% of conduits has a criticality below 0.2. Critical elements by costs of conduit reconstruction are identified as critical by the hydraulic functioning as well. Finally, the correlation (τ_b) between the criticalities of the hydraulic network functioning and 'damage to buildings' is 0.09, showing that there is no relation between the outcomes. In other words, the results of the conduit criticality for 'damage to buildings' and water distribution network system functioning are independent.

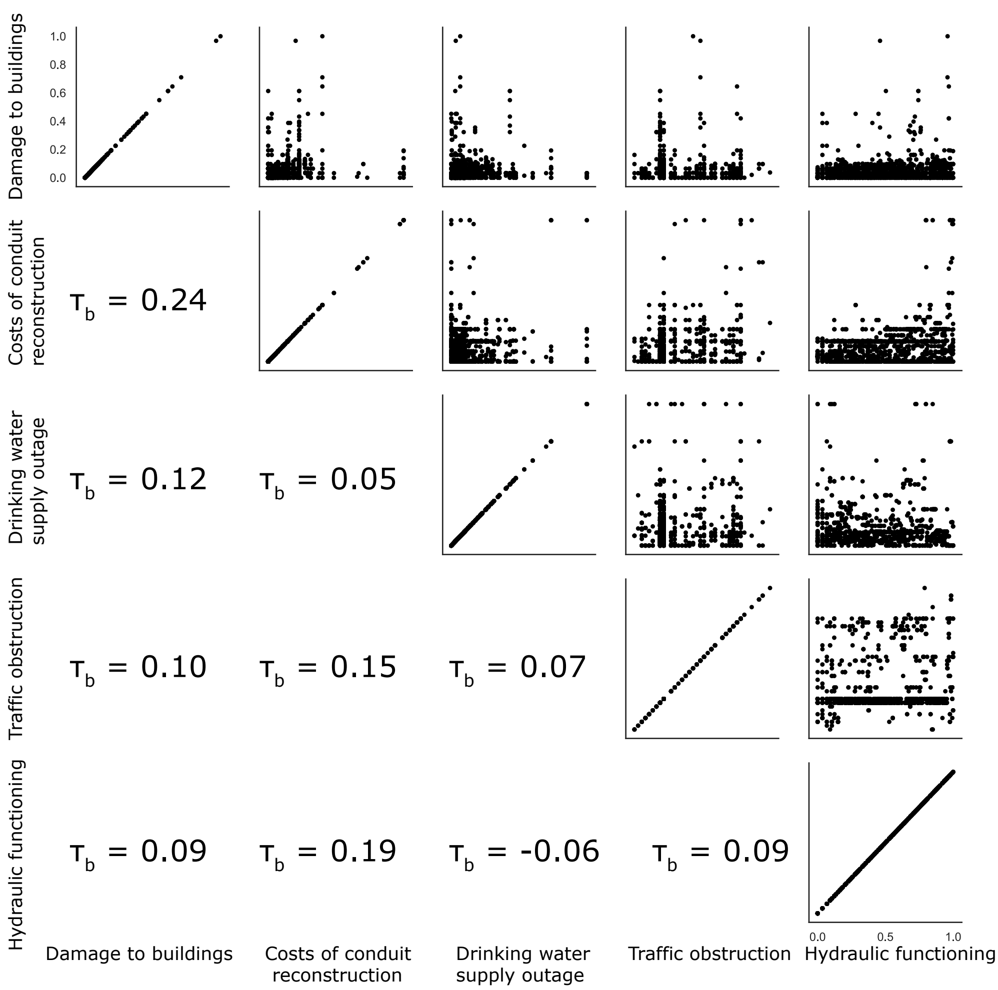


Figure 4.15: Overview of the correlation of conduit criticality based on the consequences of water distribution network failure and the hydraulic system functioning

5 Discussion

This chapter discusses the methodology and results of the research. Section 5.1 presents a discussion of the study area. The acquired results are reviewed for their quality and limitation in Section 5.2. Subsequently, Section 5.3 discusses of the validity of the combined results. The chapter concludes with a discussion on the consequences of failure within the risk determination, and its value to guide asset management.

5.1. Study area

The development process and methodology are tested on a research catchment in Tuindorp, Utrecht. This enabled it to compare results to previous studies performed in this area (Dirksen, 2013, Meijer et al., 2020, 2018, Van Bijnen et al., 2018). A disadvantage of this area is that it contains low height differences, and therefore the results provide only an indication of underground water infrastructure failures for relatively flat areas in The Netherlands. Tuindorp is a neighbourhood with multiple green spaces, front gardens and few apartment buildings. In study areas with another geographic layout results of the consequence categories could be different. Nevertheless, it is found that this study area is (geographically) representative for urban areas in The Netherlands.

Furthermore, the assumption is made that the location of (underground) infrastructure and buildings is up to date. Incorrect classification of either the underground infrastructure or the ground above could lead to errors.

5.2. Accuracy of results

5.2.1. Affected area

Flooded area

The modelling study provides insight into the water flows and the extent of the flooded area. Since a model never represents reality perfectly, this will inevitably lead to inaccuracies. The main limitation of the model was the running time. Hence, assumptions are made regarding the flood volume and locations of failure.

The flood volume in case of water distribution network failure depends on the (outflowing) water velocity and diameter of the conduit. Water velocities and outflow rates can be variable, resulting in differences in flood volumes, flooded area and thus different consequences. The flood volume in case of hydraulic sewer failure depends on, among others, the state of the sewers and previous precipitation events. The flood volume is estimated at $15m^3$, which is derived from studies of Van Bijnen et al. (2018) and De Man (2014) and verified using SOBEK flood models. For the study area in Tuindorp, the assumption is valid. The flooded area often stays within the boundaries of the sidewalks, where consequences are little sensitive. However, extreme events will inevitably lead to other consequences. For example, no flooding in case of failure will not lead to consequences as studied within this research, while an extreme flood volume will lead to substantial damages.

There are model assumptions regarding the location of failure. For the water distribution network, the failure is assumed to be located in the middle of the conduit. Regarding sewer systems, flooding occurs at the location of manholes. Failure at other locations - for example, between conduit connections - will lead to a different area flooded and could lead to different consequences.

Sinkhole area

For the sinkhole analysis, equations and data were carefully selected (Section 3.2.2), although uncertainties will still be present. Assumptions in model input and equations could result in uncertainties in sinkhole sizes. With sufficient information on system characteristics (water distribution network) and shear angle (sewer system), the approximation of the sinkhole sizes could be improved. However, more data may lead to more complex formulations and more degrees of freedom.

The sinkhole areas and consequences were estimated over the whole conduit length. Subsequently, average damages are determined by correcting the damages for the size of the sinkhole area. When the location of failure could be specified - for example, at connections or in the middle of conduits - a more realistic estimation of the consequences can be done.

5.2.2. Consequence categories

Damage to buildings

The extent of the affected area in combination with the location of buildings determines the 'damage to buildings'. The results are sensitive to the extent of the flooded area and the sinkhole size. As the flood volume often stays within the boundaries of the sidewalks, results are only sensitive when the flood volume extends the boundaries of the sidewalks. A larger sinkhole size increases the number of buildings damaged. When the approximation of the affected area can be improved, results could be more accurate.

Geographically, conduit sections that lead to damage in case of failure are often located closer to buildings than conduits without damage. For example, the segment which causes the most damage for sewer systems is located at 10cm from housing, while the average distance is about 10m.

A limitation of this method is that the vulnerability of buildings is only determined based on the presence of buildings within the affected area. The characteristics of buildings, such as construction type, are thereby not taken into account when determining the 'damage to buildings'. These characteristics are assumed to be equal for buildings in The Netherlands. However, differences in these characteristics could lead to a different amount of damage.

The analysis presents the sum of damages (0-76). Here, no (economic) distinction between different building categories is made. For example, a damaged building may either be a shed or a train station, where both are counted as one. It results in an objective view and the possibility for decision-makers to determine the value per category.

Traffic obstruction

Failure of the water distribution network causes more damage to road infrastructure compared to structural sewer failure. Most damages occurred at 'local road' for the sewer system and 'sidewalk' for the water distribution network, which is explained by the location of the network: the sewer network is located under the main or local road, whereas the water distribution network is located under the sidewalk. The results of traffic obstruction are not sensitive to the area of a sinkhole, for both structural sewer and water distribution network failure. The only road type sensitive to traffic impact is 'parking space'. Variable water depth in case of hydraulic sewer failure leads to a significant change in average obstruction, although the correlation between results is still positive. Besides, hydraulic failure leads to minimal traffic obstruction compared to structural sewer and water distribution network failure.

The analysis of traffic obstruction describes criticality of conduits for traffic congestion, based on 'sorting variables'. A limitation of this method is that the order of importance of road types could change results. However, it was found that different orders of importance did not lead to significant changes in conduit criticality. Besides, changes occurred in the conduit segments, which are not stated as critical (<0.2).

Impact on human health

Results of the health analysis are variable. Firstly, 68% of the conduits do not lead to flooding in case of failure and thus will not lead to infections. Secondly, the resulting 32% that lead to infections range between 0.16 and 319 possible infections. Pipes can cause flooding at multiple manholes in case of failure, leading to a large flooded area and a high number of infections. Outcomes can be compared with the results of Van Bijnen et al.

(2018). Both show a high infection risk in the eastern side of the catchment, where population densities are higher. In other words, infection risk is higher at locations with high population density, such as flat buildings. Contradictory, a high infection risk in the northwestern part of Tuindorp, is only shown by Van Bijnen et al. (2018) and is not valid for this study. In this study, the higher number of children in the western part of the catchment does not lead to more infections, due to the low population density and a small number of manholes flooded in case of failure.

Uncertainties on the impact on human health can be caused by the buffer. The buffer - used to test the number of people that get in contact with floodwater - is assumed to be round and variable, from 10 up to 25m. This assumption is valid for the study of Tuindorp, as the distance between buildings in different streets is more than 25m. This results in a 1% counting error for health analysis. In other areas, buildings could be located within a 25m radius. This might affect the number of people that get in contact with the floodwater and therefore, should be taken into account when performing the analysis.

Costs of conduit reconstruction

Results showed that reconstruction costs for sewer systems are higher compared to the water distribution network. Reconstruction costs are mainly determined by road pavement, where costs for asphalt roads are higher than for pavement. Since the area mainly consists of asphalt roads, costs for the renewal of sewer conduits are relatively high in Tuindorp.

Costs of conduit reconstruction depend on, among others, the length of the conduit. In this research, the maximum replacement length is assumed to be 10m. Besides, minimal replacement costs are €250 for the failure of the water distribution network. These assumptions are valid for the order of conduit criticality. However, the exact costs may be different with different replacement lengths and minimal costs.

Drinking water supply outage

Results of the consequences category supply outage show an average duration outage (OLM) of 52s, with a maximum of 6.40min. To compare these outcomes, average OLM to strive for is 14min per year, according to Vitens (2018). Therefore, one event can have a significant contribution to the total outage duration. Considering that inhabitants that experience too low water pressure are not taken into account, this number may even be higher.

In this method, the OLM per conduit was determined. A limitation of this method is that only households that do not have access to the water supply are taken into account. In other words, households that experience low water pressure are not taken into account. When these households would be taken into account, this could lead to a different range of priorities.

5.3. Combined results

The individual consequences of sewer structural failure are uncorrelated. Besides, water distribution network failure did not show similarities between individual consequences. Results of the consequence analyses show that the different consequences are independent and can not be linked. Moreover, there is no correlation found with the diameter, or in other words, a conduit with larger diameter does not lead to more damages. The geographical location and vulnerability could explain the fact that conduits do not show corresponding results on the criticality for consequences. For example, locations where segments lead to damage to main roads, do not lead to damage to buildings. The conduit may, therefore, be critical for 'traffic obstruction', though not for the 'damage to buildings'.

The hydraulic network functioning and consequence categories showed no correlation for both the sewer structural failure and water distribution network failure. Besides, the results of the hydraulic network functioning and the consequences of failure show little geographic overlap. A limitation of this method is that only overlapping conduits could be taken into account when calculating the correlation. The hydraulic network functioning does not identify multiple elements stated as critical for the consequences of water distribution network failure. When all items could be taken into account, this could result in a different correlation.

In the case of hydraulic sewer failure, all individual consequence categories show a positive relation. In general, 67% of the conduits do not lead to flooding in case of failure and thus no consequences. When a conduit does lead to flooding, the flooded area is large and causes damage to buildings, impact on human health and traffic obstruction.

The conduit criticality of the hydraulic network functioning in combination with the consequences of hydraulic sewer failure shows a pattern. Although correlation factors are only slightly positive, the figure displays two peaks for critical elements. Conduits with large diameters in main sewers are found critical for both methods (left peak), while dead-end segments are only critical for system functioning (right peak). Dead-end segments are often small, leading to a minimal affected area and resulting in minimal consequences. Therefore, dead-end sections are not found crucial for consequences of hydraulic sewer failure.

5.4. Interpretation of results

5.4.1. Consequence analysis

This study provides an overview of the consequences of failure. Only consequences that can be assessed by hydraulic modelling and (open) classified data are taken into account. Hence, this study does not include all possible consequences. Other (social) consequences of failure are not studied, such as stench and people's opinion about failures (see Table 2.1). Besides, it is assumed that the consequences are static. In other words, dynamic behaviour is not taken into account, such as driving into a sinkhole. When all consequences would be taken into account, this may lead to a different order in conduit criticality.

For objectivity of the study, (economic) values of the failure consequences are not taken into account. However, for decision making, it is needed to rate the consequences, to prioritise maintenance and rehabilitation works. Moreover, this could improve the applicability of the results. Despite these shortcomings, the methods presented within the research represent a broad framework to determine consequences, which may be applied at other locations.

5.4.2. Risk assessment

Risk is defined as the probability multiplied by the consequences of failure. For the completion of the risk determination, the failure probability should be taken into account. A rough risk assessment can be done using the results of this study and the index numbers of failure probability, as stated in Section 2.4.1. For the case study, the consequences per failure mechanism are determined. To estimate the number of critical segments within the study area, 'high-risk conduits' are defined. Asset owners are required to perform proactive maintenance for conduits identified as critical (Figure 1.1).

For sewer systems, a failure probability of 0.01 per km per year is taken into account when performing the risk assessment. The combination of the normalised consequence categories results in a maximum consequence number of 1.9 for structural sewer failure and 2.7 for hydraulic sewer failure. The total combined risk ranges between 0 and 0.03. Conduits with a risk larger than 0.015 are stated as 'high-risk conduits'. The percentage of high-risk conduits in case of structural sewer failure is 3%, while for hydraulic sewer failure this percentage is 2.3%. The current renewal rate of sewers is 0.6% per year (Gemeente Utrecht, 2017). If only proactive maintenance would be taken into account, this implies that high-risk sewer conduits would be maintained every 4 or 5 years.

For water distribution networks, the likelihood of failure depends on the material type, with failure probabilities of 0.1 (AC) and 0.1 (PVC) per km per year. The combination of the normalised results of the four consequence categories has a maximum of 3.2. The combination of the probability with the consequences result is a risk between 0 and 0.2, for the Tuindorp study area. Conduits with a risk larger than 0.1 are assumed to be at high-risk. For Tuindorp, 4.6% of the water distribution conduits is stated as a high-risk conduit.

6 Conclusions & recommendations

In this chapter conclusions of the research are presented, answering the main research question. Subsequently, Section 6.2 explains the recommendations for asset owners and further research.

6.1. Conclusions

The study aimed to develop a methodology for mapping consequences of underground water infrastructure failure to guide asset management. Therefore, three consecutive research questions were defined: 1) What are the possible consequences of hydraulic and structural failure of underground water infrastructure? 2) How can the consequences of failure be assessed, using hydraulic modelling and (open) classified data? 3) What is the effect of the individual consequences of failure on the conduit criticality in underground water infrastructure? In this section, the major findings are summarised to answer these questions.

There are five consequence categories taken into account within this research, which can be assessed using hydraulic modelling and (open) classified data. The consequence categories are: 1) Damage to buildings 2) Traffic obstruction 3) Impact on human health 4) Costs of conduit reconstruction 5) Drinking water supply outage. For the study area in Tuindorp (Utrecht), findings of the consequences of failure are illustrated and compared with the results of the hydraulic network functioning according to the Graph Theory method (GTM). This GTM determines the effects of failure of individual conduits on the functioning of a system as a whole, based on a simplified network structure using links and nodes.

Within this study, three failure mechanisms are taken into account: structural sewer failure, hydraulic sewer failure and water distribution network failure. The affected area and consequence categories differ per failure mechanism. Therefore, conclusions are drawn per failure mechanism.

Sewer - structural failure

Structural sewer failure leads to partial or complete loss of the load-carrying capacity, resulting in the formation of sinkholes. The consequences depend on the location of failure within the built environment and the sinkhole size. To illustrate: more damage occurs with a large sinkhole size in a crowded neighbourhood, compared the damage caused by a small sinkhole in a dead-end street. Due to the relative small sinkhole sizes in case of sewer structural failure, consequences are often inconsequential. For the case study, minimal damage to buildings occurs. The conduits that cause most damages are located close (at 10cm) to buildings. Regarding the traffic obstruction, structural sewer failure often leads to obstruction of local roads and sidewalks. The most critical conduits within this category are located below the main roads. Thirdly, costs for sewer replacement are relatively high, due to the high percentage of asphalt roads in the study area.

Different consequences do not show similarities in spatial patterns and criticality of segments. For example, conduits located close to buildings lead to a high number of buildings damaged, yet these conduits result in minimal traffic obstruction, as they are not located near main roads or railways. Hence, there is no relationship between the outcomes of individual consequences: different consequences lead to a different prioritisation scheme. Besides, the consequences of structural sewer failure in combination with the hydraulic network functioning lead to a significant change in the order of the criticality of sewer conduits.

Sewer - hydraulic failure
Hydraulic sewer failure refers to the internal failure of conduits, such as a blockage. The sewer system may not function properly in case of hydraulic failure, leading to flooding of streets. The extent of flooding is variable, ranging from no flooding up to flooding of half the study area. This leads to major differences in results for all consequences of hydraulic sewer failure: damage to buildings, traffic obstruction and impact on human health. In the study area, most damages occur near locations of weirs, where combined sewer overflows (CSOs) take place in case of heavy precipitation events. Here, large areas are flooded in case of hydraulic sewer failure. Besides, locations with a high amount of consequences are characterised by high population densities.

It can be concluded that conduits with large diameters in the main sewers are critical for both the analyses of the individual consequences and hydraulic functioning of the network according to the GTM. However, dead-end segments are only stated as critical by the hydraulic network functioning. When both analyses are combined, the order of conduit criticality changes such that conduits with large diameters become more significant than dead-end segments.

Water distribution network
Failure in the water distribution network leads to an affected area consisting of local flooding and sinkhole formation at the location of the failure. The consequences depend on this affected area and the exact location of the failure. The affected area is often substantial, resulting in significant consequences. Determined consequences are damage to buildings, traffic obstruction, costs of conduit reconstruction and drinking water supply outage. In Tuindorp, the flooded area and sinkhole area cause damage to different buildings; a building damaged by a sinkhole is not damaged by the flooded area. Most damage occurs when a conduit is located close (at 1m) to buildings. Traffic obstruction mainly causes blockage of local roads, sidewalks and parking spaces. Since parking spaces are often located at borders of the affected area, only this type is sensitive to the extent of the affected area. The results of reconstruction costs show a pattern of critical conduits along the main roads, where conduits with large segment lengths (>10m) and diameters (>400mm) are located. Regarding drinking water supply outage, main roads are identified as most critical when minimal valves are placed. The more valves are placed, the less damage occurs.

It can be concluded that the results of the consequence analyses lead to a significant change in the order of criticality of segments, compared to the hydraulic network functioning. Besides, the outcomes of the individual consequences are independent, leading to a different prioritisation scheme per consequence.

In conclusion, in this research a methodology is developed to map the consequences of underground water infrastructure failures. The consequences of failure inevitably lead to a different order of conduit criticality compared to the criticality based on the hydraulic network functioning. Moreover, the research results show that individual consequences are independent; it depends on the failure mechanism and consequence category, whether a conduit segment is critical or not. All consequence categories and all failure mechanisms need to be included in order to provide risk-based asset management.

6.2. Recommendations

6.2.1. Recommendations for asset owners

Complete the risk determination by adding the likelihood of failure
This research contributes to the development of risk-based asset management by investigating the consequences of failure. Risk is defined as the probability of failure multiplied by the consequences. Based on this definition, practitioners should consider adding the likelihood of failure to complete the risk assessment. For sewer systems, the likelihood of failure can be determined using an ageing model and by inspections. For water distribution networks, failure frequency data can be used to ascertain the probability of failure. The combined results of both the consequences and probability of failure can be used to develop a risk matrix to rank the conduit segments for maintenance and rehabilitation works.

Implement the analysis of failure consequences in future projects
The knowledge of failure consequences could help future (maintenance) projects in paying attention to specific conduits within a neighbourhood. Recommendations can be provided to ensure that the consequences of failure are minimal. Regarding sewer systems, proactive maintenance and sharpened quality requirements

should be applied for conduits resulting in large flooded areas near apartment buildings or areas with high population density, due to high infection risks. The costs of conduit reconstruction under asphalt roads are substantial. Therefore, when conditions allow, critical conduit segments should be located under paved roads. For water distribution networks, a sufficient amount of valves should be placed at locations with a high impact in case of failure, whereas valves could be removed when the consequences are insignificant. Depending on the consequences of reconstruction costs, traffic obstructions and damage to buildings, sewer and water distribution conduits should be located either closer or further away from buildings.

Despite research considerations, practitioners could determine the affected area using simplified methods. For the sewer structural and water distribution network failure mechanisms, the affected area can be determined by simple calculations of sinkhole sizes. For hydraulic sewer failure, the flooded area can be approximated using the results of hydraulic functioning according to Graph Theory method, provided that the catchment area is relatively flat. These simplified methods ensure that the analyses of the affected area are feasible within a limited amount of time.

6.2.2. Recommendations for further research

Improve the analyses of the affected area
It would be valuable for future studies to focus on the determination of the affected area. The outcomes of the consequence categories can be sensitive to the extent of the affected area. Improving existing methods contributes to a more precise determination of the affected area. For the applicability of the study, calculation times to determine the flooded area need to be reduced.

Enrich the analyses of the consequences of failure
To improve the implications of the results, future studies could address other consequences and the interpretations of consequences, rather than the technical outcomes as stated within this research. The analysis of failure consequences could be enriched by adding social consequences of failure, such as stench or people's opinion about conduit failure (risk perception). Moreover, dynamic consequences could be taken into account, such as the impact of vehicles driving into a sinkhole.

For decision-makers, it is needed to rate the consequence categories based on their (economic) value in order to ensure the applicability of the proposed methods. It is, therefore, useful to study the decision process and to include 'importance factors' to the different consequence categories when prioritising maintenance and rehabilitation works.

Bibliography

Aberkrom, M., Van Grunsven, R., and Langenhuijsen, K. (2016). *Assetmanagement in Waterstad. Handreiking assetmanagement stedelijk water.* STOWA, Stichting Rioned.

Adeosun, O. (2014). Water distribution system challenges and solutions. `https://www.wateronline.com/doc/water-distribution-system-challenges-and-solutions-0001`. Accessed: 2019-11-06.

Al-Hashemi, H. and Baghabra Al-Amoudi, O. (2018). A review on the angle of repose of granular materials. *Powder Technology*, 330:397 – 417. doi: 10.1016/j.powtec.2018.02.003.

Anbari, M., Tabesh, M., and Roozbahani, A. (2017). Risk assessment model to prioritize sewer pipes inspection in wastewater collection networks. *Journal of environmental management*, 190:91–101. doi: 10.1016/j.jenvman.2016.12.052.

Blokker, M., Agudelo-Vera, C., and Mesman, G. (2018). Drinking water demand under stressed conditions; quantification with simdeum. *WDSA/CCWI Joint Conference Proceedings*, 1. `https://ojs.library.queensu.ca/index.php/wdsa-ccw/article/view/12129`. Accessed: 2019-10-23.

Burian, S. and Edwards, F. (2002). Historical perspectives of urban drainage. *Global Solutions for Urban Drainage*. doi: 10.1061/40644(2002)284.

Canon van Nederland (n.d.). Tuindorp. `https://www.entoen.nu/nl/utrecht/regio-noordwest/maartensdijk/tuindorp`. Accessed: 2020-01-20.

COELO (2020). Landelijk tarievenoverzicht met gemiddelden. `https://www.coelo.nl/index.php/wat-betaal-ik-waar/tarievenoverzicht`. Accessed: 2020-07-09.

Daal, K. V., Vogelaar, A., and Mesman, G. (2011). *Inventarisatie risicovolle leidingen in een stedelijke omgeving.* KWR.

Davies, J., Clarke, B., Whiter, J., and Cunningham, R. (2001). Factors influencing the structural deterioration and collapse of rigid sewer pipes. *Urban water*, 3(1):73–89. doi: 10.1016/S1462-0758(01)00017-6.

De Man, H. (2014). *Best urban water management practices to prevent waterborne infectious diseases under current and future scenarios.* PhD thesis, Delft University of Technology.

De Wit, M., Koopmans, M., Kortbeek, L., van Leeuwen, N., Bartelds, A., and Van Duynhoven, Y. (2001). Gastroenteritis in sentinel general practices, the netherlands. *Emerging infectious diseases*, 7(1):82. doi: 10.3201/eid0701.010113.

Deltares (2020). *Delft3D-Flexible Mesh Suite user manual.* Delft, 1.5.0 edition.

Deltares (n.d.a). Delft3d. `https://oss.deltares.nl/web/delft3d`. Accessed: 2020-01-06.

Deltares (n.d.b). Sobek suite. `https://www.deltares.nl/en/software/sobek/`. Accessed: 2020-01-24.

Dirksen, J. (2013). *Monitoring ground settlement to guide sewer asset management.* PhD thesis, Delft University of Technology. doi: 10.4233/uuid:26116a82-51be-4474-853b-926f1a8f16f7.

Drinkwaterwet (2015). `https://wetten.overheid.nl/BWBR0026338/2015-07-01`. Accessed: 2020-07-08.

Elshof, L. (2015). Verborgen gevaren: Incidenten met leidingen nopen tot waterbedrijven tot innovatie asset management. *WaterForum*, 5:32–35. `https://edepot.wur.nl/409467`. Accessed: 2019-09-15.

Engelhaupt, E. (2017). Huge blobs of fat and trash are filling the world's sewers. *National Geographic*, 10. `https://www.nationalgeographic.com/news/2017/08/fatbergs-fat-cities-sewers-wet-wipes-science/`. Accessed: 2019-09-20.

Fenner, R. A., Sweeting, L., and Marriott, M. J. (2000). A new approach for directing proactive sewer maintenance. *Proceedings of the Institution of Civil Engineers - Water and Maritime Engineering*, 142(2):67–77. doi: 10.1680/wame.2000.142.2.67.

Geels, F. (2006). The hygienic transition from cesspools to sewer systems (1840-1930): The dynamics of regime transformation. *Research Policy*, 35(7):1069 – 1082. doi: 10.1016/j.respol.2006.06.001.

Gemeente Utrecht (2017). Plan gemeentelijke watertaken utrecht. `https://www.utrecht.nl/fileadmin/uploads/documenten/bestuur-en-organisatie/publicaties/begroting_en_verantwoording/2017/Begroting2017_ORG_Gemeentelijke-Watertaken-Utrecht.pdf`. Accessed: 2019-11-06.

Gemeente Utrecht (n.d.). Gladheidbestrijding en strooizout. `https://www.utrecht.nl/wonen-en-leven/verkeer/gladheidbestrijding-en-strooizout/`. Accessed: 2020-03-03.

Gray, H. (1940). Sewerage in ancient and medieval times. *Sewage Works Journal*, 12:939–946. `http://sewerhistory.orgwww.sewerhistory.org/articles/whregion/1940_as201/article1.pdf`. Accessed: 2019-10-01.

GreenBlue Urban (2017). The history of urban drainage. `https://www.greenblue.com/na/history-urban-drainage/`. Accessed: 2019-09-30.

Jonkman, S., Steenbergen, R., Morales-Nápoles, O., Vrouwenvelder, A., and Vrijling, J. (2018). Probabilistic design: Risk and reliability analysis in civil engineering. Lecture notes CIE4130.

Kadaster (2020). Bag viewer. `https://bagviewer.kadaster.nl/lvbag/bag-viewer/`. Accessed: 2020-03-12.

Kaplan, S. and Garrick, J. (1981). On the quantitative definition of risk. *Risk analysis*, 1(1):11–27. doi: 10.1111/j.1539-6924.1981.tb01350.x.

Karoui, T., Jeong, S., Jeong, Y., and Kim, D. (2018). Experimental study of ground subsidence mechanism caused by sewer pipe cracks. *Applied Sciences*, 8:679. doi: 10.3390/app8050679.

Kendall, M. (1945). The treatment of ties in ranking problems. *Biometrika*, 33(3):239–251. doi: 10.1093/biomet/33.3.239.

King Fahd University of Petroleum and Minerals (n.d.). Ce370: Water distribution networks. `https://faculty.kfupm.edu.sa/CE/abukhari/Courses/CE370/Lectures/Water%20Distribution%20System.pdf`. Accessed: 2019-11-06.

Kiwa (2005). Evaluatie pilot ondermaatse leveringsminuten. `https://edepot.wur.nl/450546`. Accessed: 2020-04-03.

Kohl, M. (2001). Subsidence and sinkholes in east tennessee. *State of Tennessee Dep't Env't Conservation: Div. of Geology*, pages 4–5. `https://www.jumpjet.info/Emergency-Preparedness/Disaster-Mitigation/Earth/Subsidence_and_Sinkholes.pdf`. Accessed: 2019-11-15.

KWR (2020). Simdeum. `https://www.kwrwater.nl/en/tools-producten/simdeum/`. Accessed: 2020-03-24.

KWR (n.d.). Ustore. `https://www.kwrwater.nl/tools-producten/ustore/`. Accessed: 2020-08-19.

Langeveld, J. (2004). *Interactions within wastewater systems*. PhD thesis, Delft University of Technology.

Liu, H., Walski, T., Fu, G., and Zhang, C. (2017). Failure impact analysis of isolation valves in a water distribution network. *Journal of Water Resources Planning and Management*, 143(7):04017019. doi: 10.1061/(ASCE)WR.1943-5452.0000766.

Mastbergen, D. (2010). *Ontgronding bij persleidingbreuk- of lek: evaluatie rekenmethode NEN 3651*. Utrecht: Deltares. Rapportkenmerk 1201743-000-ZKS-0002.

Meijer, D., Post, J., van der Hoek, J., Korving, H., Langeveld, J., and Clemens, F. (2020). Identifying critical elements in drinking water distribution networks using graph theory. *Structure and Infrastructure Engineering*, 0:1–14. doi: 10.1080/15732479.2020.1751664.

Meijer, D., Van Bijnen, M., Langeveld, J., Korving, H., Post, J., and Clemens, F. (2018). Identifying critical elements in sewer networks using graph-theory. *Water (Switzerland)*, 10. doi: 10.3390/w10020136.

Ministerie van Binnenlandse Zaken en Koninkrijksrelaties (2011). Bouwbesluit 2012.

National Research Council (2006). *Drinking Water Distribution Systems: Assessing and Reducing Risks.* The National Academies Press, Washington, DC. doi: 10.17226/11728.

NEN 3651 (2012). *Aanvullende eisen voor buisleidingen in of nabij belangrijke waterstaatswerken.* NEN Connect.

NIBHV (2016). 15 miljoen liter water teisterde vumc. *Veiligheid*, 67:6–9. http://www.technisch-tekstwerk.nl/wp-content/uploads/2016/11/NIBHV-Veiligheid-67-wateroverlast-VUMc.pdf. Accessed: 2019-09-23.

Oxford University Press (2020). Oxford advanced learner's dictionary. https://www.oxfordlearnersdictionaries.com/definition/english/risk_1. Accessed: 2020-01-03.

Piratla, K., Yerri, S., Yazdekhasti, S., Cho, J., Koo, D., and Matthews, J. (2015). Empirical analysis of water-main failure consequences. *Procedia Engineering*, 118:727–734. doi: 10.1016/j.proeng.2015.08.507.

Post, J. (2016). *A statistical approach to guide the management of the anterior part of the sewer system.* PhD thesis, Delft University of Technology. doi: 10.4233/uuid:8cb16d1a-44e0-4798-b638-88b5b74d6bd6.

Provincie Utrecht (n.d.). Bodemkaart vereenvoudigd. https://webkaart.provincie-utrecht.nl. Accessed: 2020-01-06.

QGIS (n.d.). Discover qgis. https://www.qgis.org/en/site/. Accessed: 2020-01-21.

Rijkswaterstaat (2019). Wet milieuhebeer. https://www.rijkswaterstaat.nl/water/wetten-regels-en-vergunningen/natuur-en-milieuwetten/wet-milieubeheer.aspx. Accessed: 2019-10-01.

Rijkswaterstaat (n.d.). Gemeentelijk rioleringsplan. https://www.infomil.nl/onderwerpen/lucht-water/handboek-water/wetgeving/wet-milieubeheer/gemeentelijk/. Accessed: 2020-07-09.

RIVM (n.d.). Bevolking, huishoudens. https://www.volksgezondheidenzorg.info/onderwerp/bevolking/cijfers-context/huishoudens. Accessed: 2020-03-12.

Salman, B. and Salem, O. (2012). Risk assessment of wastewater collection lines using failure models and criticality ratings. *Journal of Pipeline Systems Engineering and Practice*, 3:68–76. doi: 10.1061/(ASCE)PS.1949-1204.0000100.

Savic, D., Giustolisi, O., Berardi, L., Shepherd, W., Djordjevic, S., and Saul, A. (2006). Modelling sewer failure by evolutionary computing. *Proceedings of the Institution of Civil Engineers - Water Management*, 159(2):111–118. doi: 10.1680/wama.2006.159.2.111.

Stanic, N., Langeveld, J., and Clemens, F. (2014). Hazard and operability (hazop) analysis for identification of information requirements for sewer asset management. *Structure and Infrastructure Engineering*, 10:1345–1356. doi: 10.1080/15732479.2013.807845.

Stichting Rioned (2010). Riool in cijfers 2009-2010.

Stichting Rioned (2015). Kostenkengetallen.

Stichting Rioned (2017). Module riolering voor het hbo.

STOWA (2018). Waterschadeschatter. https://www.waterschadeschatter.nl/damage/. Accessed: 2020-01-06.

ten Veldhuis, J., Clemens, F., and van Gelder, P. (2011). Quantitative fault tree analysis for urban water infrastructure flooding. *Structure and Infrastructure Engineering*, 7(11):809–821. doi: 10.1080/15732470902985876.

Tscheikner-Gratl, F., Sitzenfrei, R., Rauch, W., and Kleidorfer, M. (2016). Integrated rehabilitation planning of urban infrastructure systems using a street section priority model. *Urban Water Journal*, 13(1):28–40. doi: 10.1080/1573062X.2015.1057174.

USGS (n.d.). Sinkholes. `https://www.usgs.gov/special-topic/water-science-school/science/sinkholes`. Accessed: 2019-11-15.

Van Bijnen, M. (2018). *The impact of sewer condition on the performance of sewer systems.* PhD thesis, Delft University of Technology. doi: 10.4233/uuid:375c1ff4-322e-42de-be6a-a3ff96420065.

Van Bijnen, M., Korving, H., Langeveld, J., and Clemens, F. (2018). Quantitative impact assessment of sewer condition on health risk. *Water*, 10(3):245. doi: 10.3390/w10030245.

Van Bijsterveld, W. (2020). Informatie buurt tuindorp. `https://allecijfers.nl/`. Accessed: 2020-03-12.

Van Riel, W. (2016). *On decision-making for sewer replacement.* PhD thesis, Delft University of Technology. doi: 10.4233/uuid:92b10448-795d-43ac-8071-d779af9d374d.

Vastelastenbond (2018). Waterprijzen 2019 | wordt de waterrekening duurder? `https://www.vastelastenbond.nl/blog/waterprijzen-2019-wordt-de-waterrekening-duurder/`. Accessed: 2019-10-03.

Vewin (2018). Dutch drinking water statistics 2017: From source to tap. `https://www.vewin.nl/SiteCollectionDocuments/Publicaties/Cijfers/Drinkwaterstatistieken-2017-EN.pdf`. Accessed: 2019-11-06.

Vinten-Johansen, P., Brody, H., Paneth, N., Rachman, S., Zuck, D., Rip, M., Zuck, D., et al. (2003). *Cholera, chloroform, and the science of medicine: a life of John Snow.* Medicine.

Vitens (2018). Jaarverslag. `https://www.vitensjaarverslag.nl/jaarverslag/hoe-we-waarde-creeren/leveren-van-kwalitatief-goed-drinkwater`. Accessed: 2020-03-24.

Vlek, C. (1996). A multi-level, multi-stage and multi-attribute perspective on risk assessment, decision-making and risk control. *Risk Decision and Policy*, 1:9–31. doi: 10.1080/135753096348772.

Vuorinen, H., Juuti, P., and Katko, T. (2007). History of water and health from ancient civilizations to modern times. *Water Science & Technology: Water Supply*, 7. doi: 10.2166/ws.2007.006.

Waterleidingwet (2009). `https://wetten.overheid.nl/BWBR0002246/2009-07-01`. Accessed: 2020-07-08.

Waterschappen, Provincies and Rijkswaterstaat (2020). Het verhaal van ahn. `https://www.ahn.nl/`. Accessed: 2020-03-30.

A

Failure mechanisms in sewer systems

Structural failure
Structural failure is the failure of elements, where the functioning of the system is no longer in tact. Structural failure can have multiple causes leading to a total collapse of the system.

1. Aging & degradation: The end of technical lifespan can lead to structural failure of piped network systems. Systems should be replaced in time to prevent this type of failure. Although most pipe systems actually have a longer lifespan than calculated, degradation is highly dependent on material properties and environmental processes.

2. Human errors: Humans do have a large influence on the state of the underground water infrastructure. Stanic et al. (2014) identified sewer failure mechanisms and causes of the failure Stanic et al. (2014). It was found out that human errors can be divided into several groups. Errors in production, design, construction, maintenance and abuse can cause structural failure of the system.

3. Increased top load: As pipes are located under urban road infrastructure, (variable) loads are present. The top load increases when, for example, a bicycle lane changes into a busy road for cars/trucks. This load increase influences the soil stability and may lead to pipe displacement.

4. Natural disaster: In the northern part of The Netherlands frequent (small) earthquakes occur, which can lead to displacement of the pipes or total collapse of the system.

5. Land settlement: Soft soil conditions are characteristics of many delta areas, for example the megacities Jakarta and Bangkok and areas in the western part of The Netherlands. The local soft soil causes soil settlements that significantly influence the vertical position of underground infrastructure and therefore the functioning of the system Dirksen (2013). Differential settlement of underground infrastructure causes the development of cracks, open joints or deformation of pipes, which may result in infiltration or (partial) collapse of the system.

Hydraulic failure
Hydraulic sewer failure includes the intern failure of a system, due to for example blockages or leakage. In general, hydraulic failure does not lead to a total breakdown of the system. In other words, the system continues functioning.

1. Climate change: According to a study of Langeveld et al. (2013) climate change can have an impact on the sewer system, where for example blockages can occur after a large dry period [23]. Besides, a change in precipitation patterns also influences the WWTP and receiving waters.

2. Human errors: Like sewer structural failure, human errors in design, production, construction and maintenance could lead to sewer hydraulic failure. First, design errors could occur when for example wrong rainfall events are taken into account when developing a sewer network. Secondly, failures could occur due to incorrect connections of pipes segments. Furthermore, operation and maintenance errors occur because of erroneous inspections or incorrect strategies of the agencies. This could also lead to abuse of the infrastructure, where maintenance should have taken place.

3. Infiltration: Fractures in pipe systems can lead to infiltration of sand and groundwater. Due to the water infiltration into the pipes, additional water flows to the WWTP. Besides, sediments can enter the pipe system which can result in blockages of pipes and backups into houses and overflows of streets.

4. Exfiltration: Being the opposite of infiltration, exfiltration of water leads to an increased amount of water in the soil. In sewer systems, sewerage could end up in the environment, resulting in contamination of the area and serious health problems.

5. Expansion of network: More connections, due to expansion of the area (housing, industry), leads to larger connected area with corresponding amount of sewage. This could lead to an overload in the current systems.

6. Root intrusion: Tree roots invade sewer pipes, seeking for water, nutrients and oxygen. The degree of root invasion depends on the tree type, soil condition (soil type, groundwater level) and pipe state (openings). This root intrusion can expand the existing opening, allowing quantities of the surrounding soil to enter through the defect. The roots themselves can have negative effects on hydraulic conditions by forming local flow restrictions, which increases the possibility of solids to be captured, which then further reduces the flow velocity. The blockages in conduits cause backups in into homes or overflows on streets.

B

Data availability

Data used within this research is presented in Table B.1. Data is either open available or assessed via the municipality of Utrecht, earlier research and the Drinking water company (DWC).

Table B.1: Data types and availability

Category	**Data type**	**Accessed from**
General	Location underground water network	Municipality, DWC
Flooded area	Elevation model	AHN
	Location gully pots	Municipality, Rioolenzo
	Location manholes	Municipality
	Flood volume	Van Bijnen et al. (2018), De Man (2014)
	Outflow velocity of drinking water	DWC
	Drainage velocity of gully pots	Municipality
Sinkhole formation	Conduit diameter	Municipality, DWC
	Conduit depth	Municipality
	Soil type	Province
	Maximum operating pressure	DWC
Damage to buildings	Location of buildings	OSM, Google Maps
	Function of buildings	Bouwbesluit, Daal et al. (2011), OSM, Google Maps
Traffic congestion	Location of road network	Municipality, OSM, Google Maps
	Function of roads	Gemeente Utrecht (nd), OSM, Municipality
Health impact	Population numbers	CBS, Van Bijnen et al. (2018)
	Infection risk	Van Bijnen et al. (2018), De Man (2014)
Reconstruction costs	Replacement costs	Stichting Rioned (2015), Municipality, DWC
Supply outage	Location of valves	DWC
	Average water usage	DWC
	Costs of water	DWC
	Duration of supply outage	DWC

C

Software

Delft3D FM
Delft3D FM is a hydrodynamic simulation program developed to perform 1D, 2D and 3D computations for coastal, river and estuarine areas Deltares (2020). It consists of multiple modules including Delft3D Flexible Mesh which calculates non-steady flow and transport resulting from tidal and meteorological forcing Deltares (nda).

SOBEK
SOBEK is a Deltares software suite that can be used for, among others, flood forecasting, optimisation of drainage systems and sewer overflow design Deltares (ndb). The module SOBEK Urban can be used control, evaluate and optimise new and current sewer systems Deltares (ndb). For this study, SOBEK Urban is used to determine the water volume on streets, in case of different storm events ('leidraadbuien').

QGIS
QGIS is a free and open source Geographic Information System (GIS) QGIS (nd). It supports analysing and editing spatial information, as well as composing and exporting graphical maps. Both raster and vector layers (point, line, polygon features) can be applied. QGIS version 3.4.14 'Madeira' long term release is used within this study. The used coordinate reference system (CRS) is of Amersfoort (EPSG:28992).

D

Delft3D model settings

The main settings of the Delft3D Flexible Mesh Suite are described in TableD.1. Default settings are not explained and can be found in the D-Flow Flexible Mesh user manual Deltares (2020). Table 3.4 shows the main input settings for the sewer system and the water distribution network.

Table D.1: Summary of the main model parameter settings in Delft3D

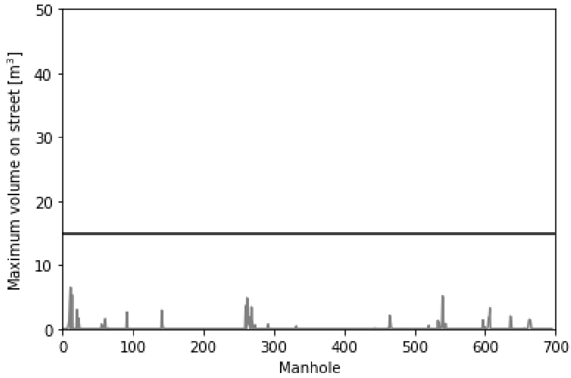
Parameter	**Keyword**	**Setting**	**Description**
Geometry	WaterLevIni	-5	Initial water level [m]
	BedLevType	1	1: at cell centre (tiles xz, yz, bl,bob=max(bl)), 2: at face tiles (tiles xu, yu, blu,bob=blu), 3: at face (using mean node values), 4: at face (using max node values), 6: with bl based on node values
Numerics	FixedWeirScheme	9	6 = semi-subgrid scheme, 8: Tabellenboek, 9: Villemonte
	Slopedrop2D	0.3	Apply droplosses only if local bottom slope > Slopedrop2D, <= 0 = no droplosses
Time	DtMax	60	Max time step [s]
	DtUser	1200	User time step (interval for external forcing update and his/map output) [s]
	TStop	3600	Stop time w.r.t. RefDate [in Tunit = s]
External forcing	ExtForceFile	*.ext (sewer or water supply)	Old format for external forcing file *.ext link with tim/cmp-format boundary conditions specification.
Output	Foufile	maxima.fou	*.fou link
	HisInterval	1200	History output, given as 'interval' 'start period' and 'period(s)'
	RstInterval	0	Restart file output, given as 'interval' 'start period' and 'period(s)'
	Wrihis_structure_gen	0	Write general structures, 1: yes, 0: no
	Wrihis_structure_dam	0	Write dams, 1: yes, 0: no
	Wrihis_structure_pump	0	Write pumps, 1: yes, 0: no

Wrihis_structure_gate	0	Write gates, 1: yes, 0: no
Wrimap_waterlevel_s0	0	Write water levels at old time level, 1: yes, 0: no
Wrimap_velocity_component_u0	0	Write velocities at old time level, 1: yes, 0: no
Wrimap_velocity_component_u1	0	Write velocities at new time level, 1: yes, 0: no
Wrimap_velocity_vector	0	Write velocities vectors, 1: yes, 0: no
Wrimap_density_rho	0	Write density, 1: yes, 0: no
Wrimap_horizontal_viscosity_viu	0	Write density, 1: yes, 0: no
Wrimap_horizontal_diffusivity_diu=	0	Write horizontal diffusivity, 1: yes, 0: no
Wrimap_flow_flux_q1	0	Write fluxes, 1: yes, 0: no
Wrimap_spiral_flow	0	Write spiral flow, 1: yes, 0: no
Wrimap_numlimdt	0	Write numlimdt, 1: yes, 0: no
Wrimap_taucurrent	0	Write bottom friction, 1: yes, 0: no
Wrimap_chezy	0	Write chezy values, 1: yes, 0: no
Wrimap_turbulence	0	Write turbulence, 1: yes, 0: no
Wrimap_wind	0	Write wind, 1: yes, 0: no
Richardsononoutput	1	Write Richardson number, 1: yes, 0: no

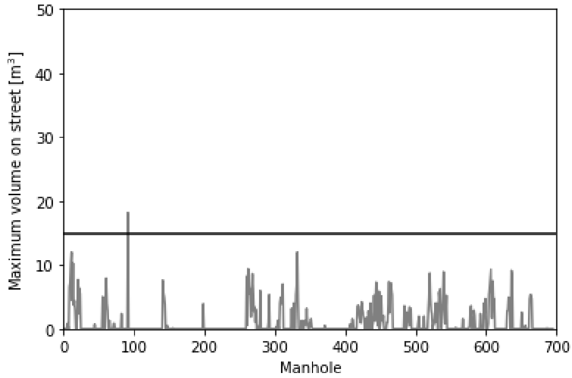
E

Flood volume on streets

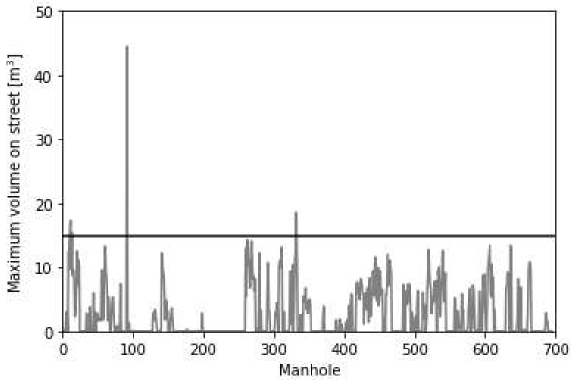
The standard precipitation events (Vlaamse Composiet Buien (VLC)) with a return period of 1, 2, 5 and 10 years are used to simulate the maximum volume on streets per manhole. Precipitation series contain rainfall events separated by periods without precipitation. Moreover, it is assumed that there are no in-sewer defects.



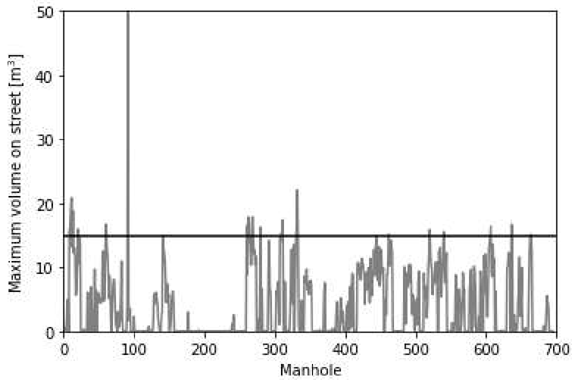
(a) Maximum flood volume, 1 year return period



(b) Maximum flood volume, 2 year return period



(c) Maximum flood volume, 5 year return period



(d) Maximum flood volume, 10 year return period

Figure E.1: Maximum flood volume per manhole in Tuindorp, for different return periods

F

Sinkhole dimensions

The radius of the sinkhole can be determined by using the calculation method and evaluation of the calculation method of the NEN3651 NEN 3651 (2012)Mastbergen (2010). Empirical formulas are used to determine the sinkhole size. Equation F.1 is the most accurate formula to calculate the radius of the sinkhole at a certain location. The demonstrated calculation method applies to completely fluid-filled pipes NEN 3651 (2012).

$$R_B = 7.8 \cdot d_g \cdot \left\{ \frac{P}{\rho \cdot g^{1.5} \cdot \mu \cdot d_g^{3.5}} \right\}^{0.243} \tag{F.1}$$

with:

R_B	= Radius of the sinkhole	[m]
d_g	= Diameter of the hole caused by leakage or failure ($0 \le d_g \le D_i$)	[m]
D_i	= Intern diameter of conduit	[m]
ρ	= Density of the liquid	[kg/m^3]
g	= Gravitational acceleration	[m/s^2]
μ	= Runoff coefficient of the hole caused by leakage or failure (= 0.6 if small hole with high pressure and 1.0 if big hole with low pressure)	[-]
P	= Hydraulic power of the outflow (= $\mu \times g \times Q \times h$)	[W]
h	= Normative pressure head at the location of the hole	[mwk]
Q	= Flow rate trough the hole	[m^3/s]

The flow rate (Q) depends on the local pressure, the size of the hole and runoff coefficient. The value of μ is determined by local pressure head and can be calculated using the following equation:

$$\mu = 0.002 \cdot h^2 - 0.02 \cdot h + 1 \text{ or } \mu = 0.5 \text{ if } h > 50 \text{ mwk} \tag{F.2}$$

Two main assumptions are made regarding Equation F.1. The stated equation is based on model tests and have been validated using practical test, with a probability value around 5% NEN 3651 (2012). Fine, saturated sand was used in the tests, as this soil type is regarded as erosion sensitive Daal et al. (2011). In highly cohesive soils, such as clay soils, sinkhole dimensions are expected to be the same or smaller Mastbergen (2010). Therefore, the assumption of fine sand gives a conservative estimation of the dimension of the sinkhole. Besides, the equation applies to a horizontal surface and a conduit with ground coverage around 5 × D_i or 3.0 m NEN 3651 (2012). For conduits deeper in the soil there will no longer be a sinkhole, but soil collapse, under the influence of fluid pressure NEN 3651 (2012).

Most realistic values of Q and h are obtained at the location of the sinkhole. As an alternative, pump characteristics can be used, where the pressure losses between the pumping station and location of the leak are assumed to be zero NEN 3651 (2012). Depending on the distance between the pumping station and leak, this approach will lead to an overestimation of the radius of the sinkhole.

G

Reconstruction costs

Table G.1: Reconstruction costs for a plain sewer conduit of 300mm

Cost category		**€/unit**	**€/m**
1. Conduit			
Material			14
Placement			6
Removal			4
Waste processing	0.18 tonne	127	23
		Subtotal 1	47
2. Earthwork			
Size hole (width x depth)*	1.30 / 1.34		
Slope	0.75 : 1		
Volume hole (m^3/m)*	3.09		
Earthwork	3.09m^3	7	22
Costs new soil	0.46m^3	9	4
Foundation conduit soil improvement			9
		Subtotal 2	34
3. Road surfacing			
Width hole (at ground level)	4.31		
Percentage pavement*	50%		
- removal €/m^2		2	4
- placement €/m^2		22	47
Percentage asphalt*	50%		
- removal €/m^2		5	11
- placement €/m^2		50	108
		Subtotal 3	170
4. Other			
Traffic measures			15
Accessibility buildings			12
Cables/trees/pipes			4
		Subtotal 4	31
Total excluding surcharges			283
5. Surcharges	0.417		118
6. Calamity factor	5%		20
Total costs			420

Table G.2: Reconstruction costs for a reinforced sewer conduit of 700mm

Category		**€/unit**	**€/m**
1. Conduit			
Material			103
Placement			10
Removal			8
Waste processing	0.625 tonne	127	79
		Subtotal 1	201
2. Earthwork			
Size hole (width/depth)*	1.70 / 2.29		
Slope	0.75 : 1		
Volume hole (m^3/m)*	7.81		
Earthwork	7.81m^3	7	55
Costs new soil	1.17m^3	9	11
Foundation conduit soil improvement			9
		Subtotal 2	74
3. Road surfacing			
Width hole (at ground level)*	6.13		
Percentage pavement*	50%		
- removal €/m^2		2	6
- placement €/m^2		22	67
Percentage asphalt*	50%		
- removal €/m^2		5	15
- placement €/m^2		50	153
		Subtotal 3	242
4. Other			
Traffic measures			32
Accessibility buildings			12
Cables/trees/pipes			4
		Subtotal 4	48
Total excluding surcharges			565
5. Surcharges	0.417		235
6. Calamity factor	5%		40
Total costs			840

* Variable per conduit

H

Results affected area

The results of the analysis on the affected area are presented. The affected area in case of sewer structural failure, hydraulic sewer failure and water distribution network failure is mapped. These results are used to determine the consequences of underground water network failure.

H.1. Flooded area

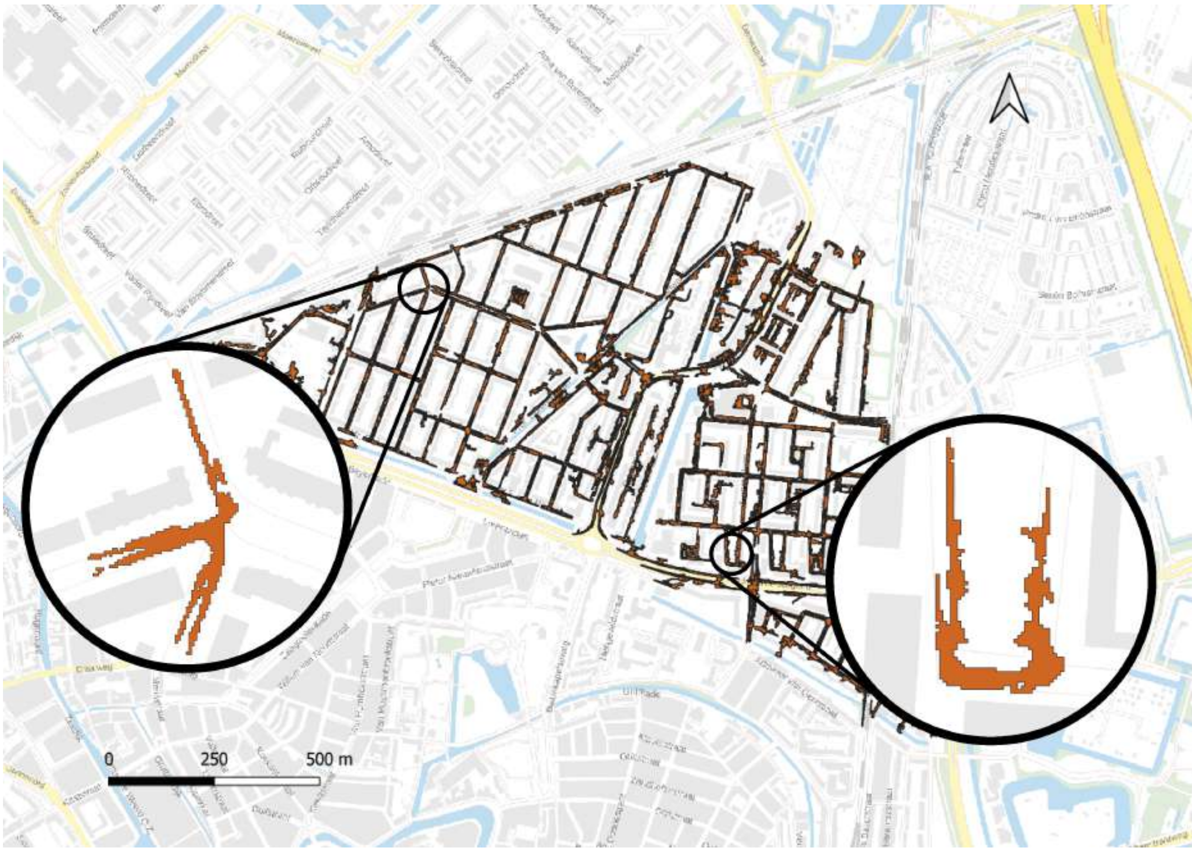


Figure H.1: Flooded area at manholes in case of sewer hydraulic failure in Tuindorp

Figure H.2: Examples of flood depth at manholes in case of sewer hydraulic failure in Tuindorp

Figure H.3: Flooded area in case of water distribution network failure in Tuindorp

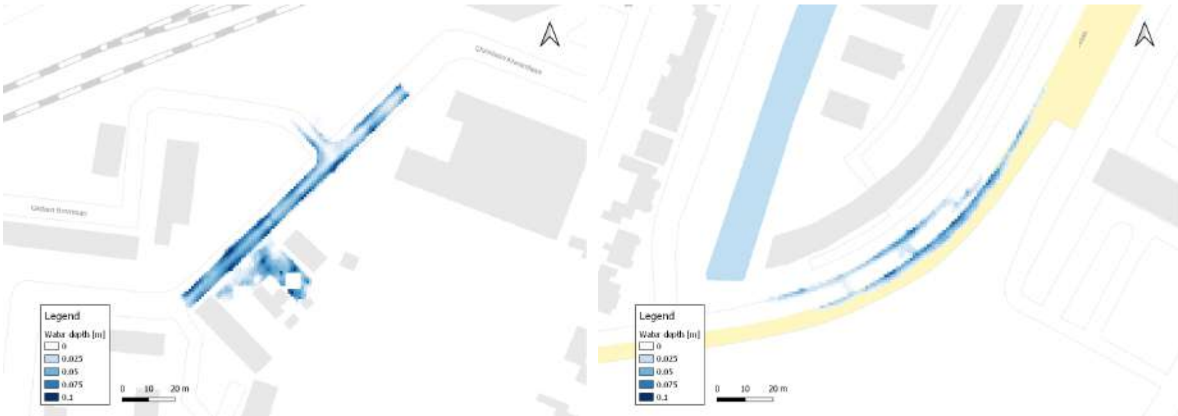


Figure H.4: Examples of flood depths at manholes in case of water distribution network failure in Tuindorp

H.2. Sinkhole area

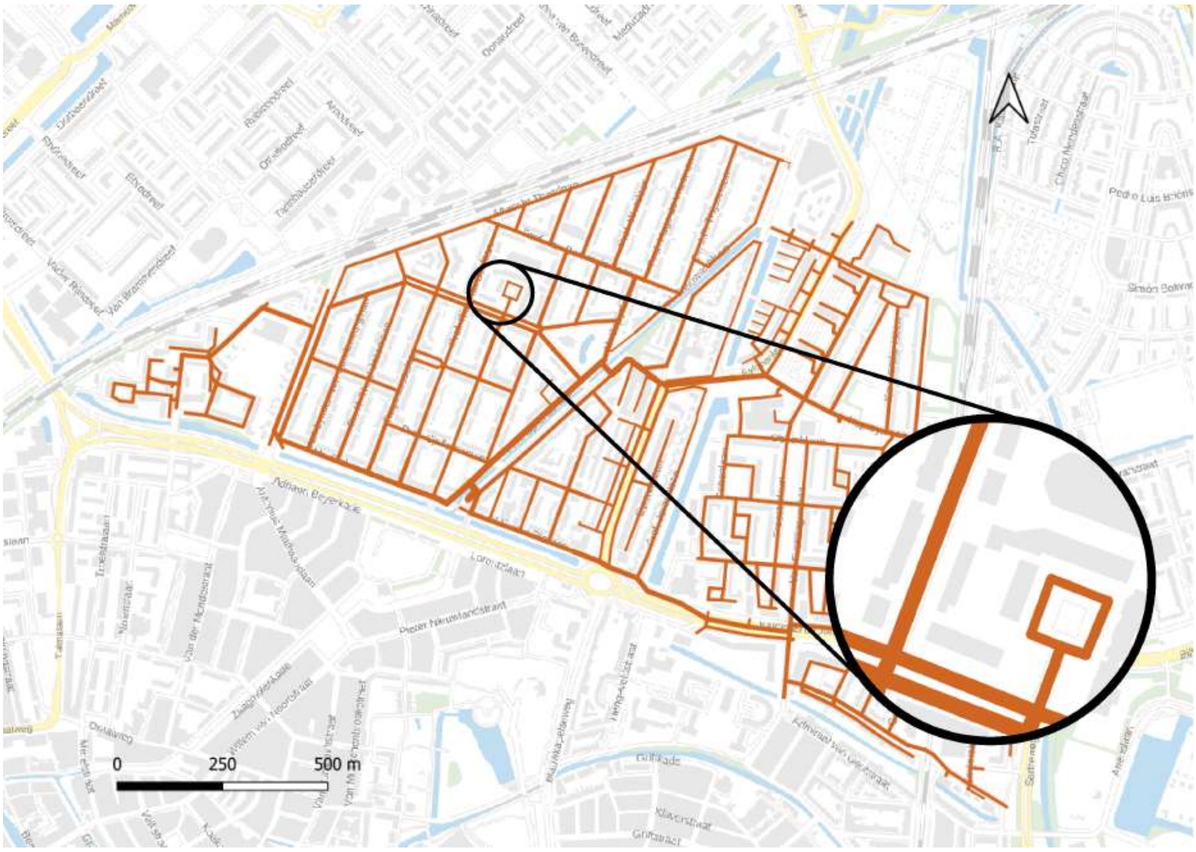


Figure H.5: Dimensions of sinkholes in case of sewer structural failure in Tuindorp

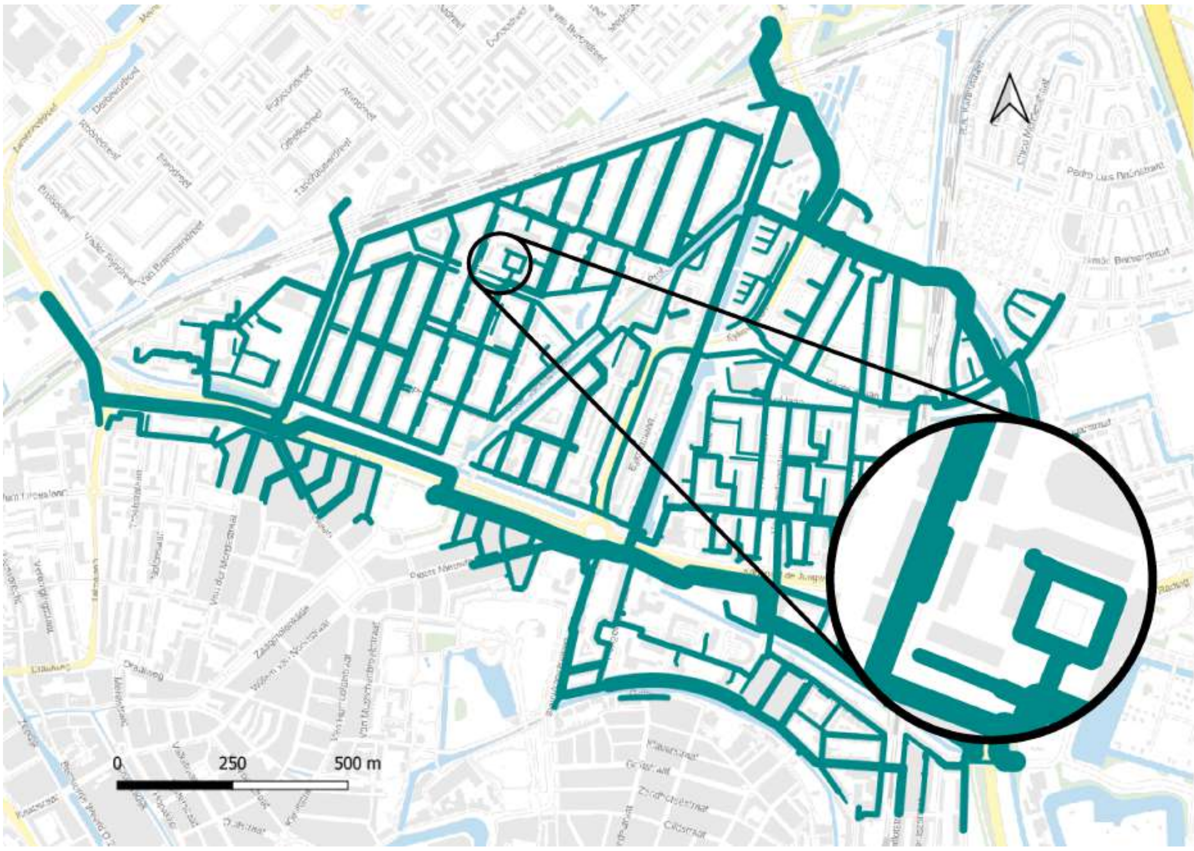


Figure H.6: Dimensions of sinkholes in case of water distribution network failure in Tuindorp