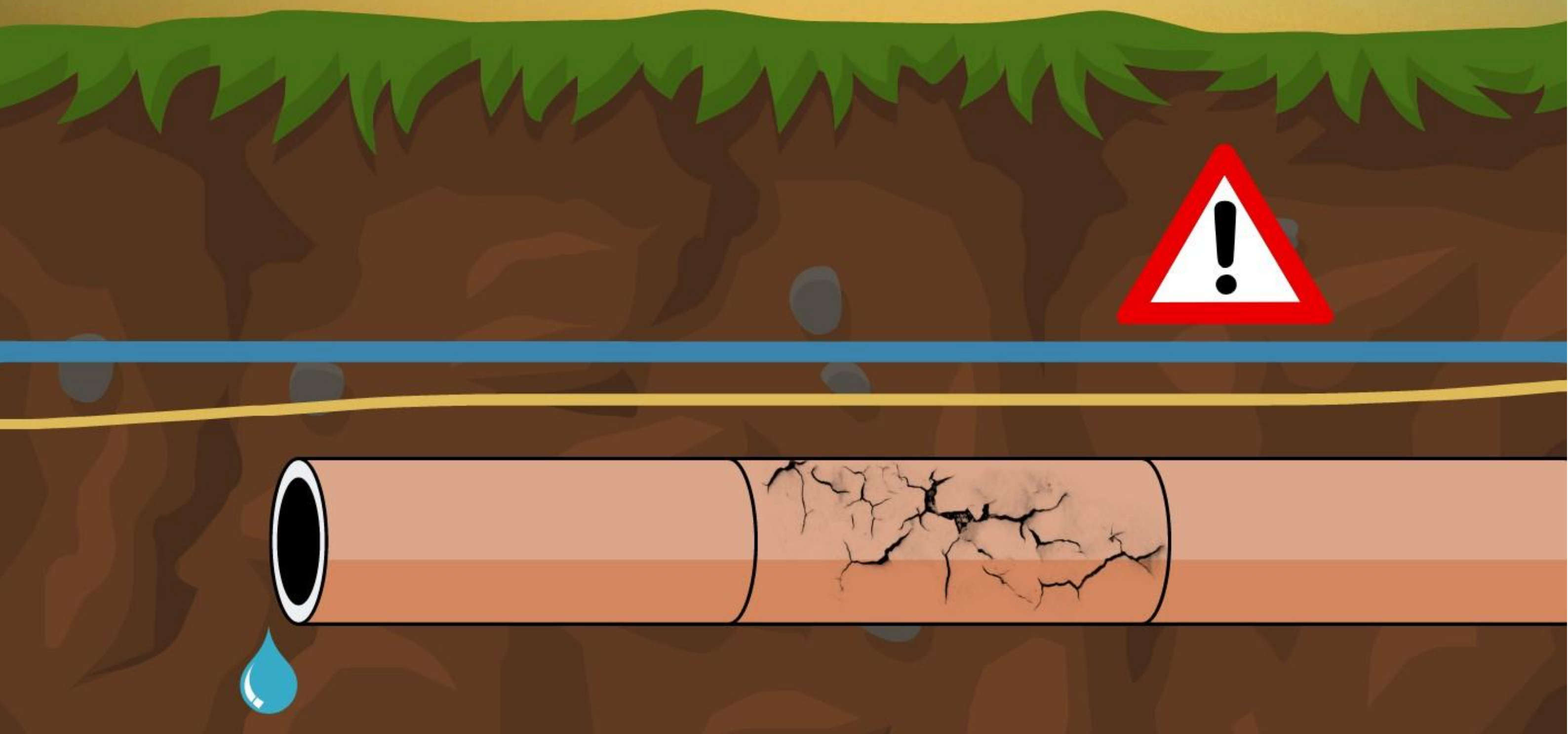
RISK-BASED SEWER ASSET MANAGEMENT

A PRACTICAL IMPLEMENTATION

M.P.Kraan



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Risk-Based Sewer Asset Management

A case study assessing the risk of sewer collapse in Nissewaard, the Netherlands

By

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To obtain the degree of Master of Science at the Delft University of Technology.

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Thesis duration:	November – July	
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ABSTRACT

This thesis examines the implementation of risk-based sewer asset management, with a specific focus on addressing the existing shortcomings in current practices. Notably, the neglect of sewer failure risks often leads to suboptimal allocation of resources. The primary aim of this research is to develop a comprehensible methodology for risk-based sewer asset management in the Netherlands. The proposed methodology employs a combined risk matrix approach to assess the level of risk associated with sewer collapse. This assessment takes into account both the probability of failure and the potential consequences of such failures. The thesis primarily focuses on the risk of sewer collapse within the context of the Netherlands. To demonstrate the applicability of the methodology, a case study is conducted in the municipality of Nissewaard. The outcomes of this case study are then compared to the conventional approach employed in Dutch sewer asset management. Through this analysis, the study emphasizes the necessity of establishing a practical roadmap for implementing risk-based sewer asset management. Additionally, recommendations are made for enhancing the objectivity of sewer inspections and developing a sewer deterioration model. The findings reveal that the adoption of risk-based asset management is more cost-effective in mitigating the risk of sewer collapse when compared to the prevailing replacement strategy. The research aims to bridge the gap between academic theory and practical application by providing a straightforward methodology grounded in prior research. In order to advance the field of risk-based approaches, this study calls for further research into the potential obstacles associated with implementing risk-based asset management. Such investigations will contribute to a better understanding of the challenges and facilitate the successful adoption of risk-based sewer asset management practices.

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1 GLOSSARY

Buffer analysis: An analysis technique that uses buffers or proximity zones to assess the relationship between spatial features or elements.

Classificatiemethodiek: This document describes the Dutch classification methodology for assessing the severity and extent of condition aspects seen during visual sewer inspections, based on the European standard NEN-EN 13508-2:2003+A1:2011.

Closed Circuit Television (CCTV): A visual inspection technique used in sewer asset management, where images or videos are captured of the sewer network using cameras.

Combined risk matrix: A framework used to assess and prioritize risks by considering the consequences of failure and the likelihood of occurrence. It uses organizational values to establish the level of severity and risk.

Condition assessment: An evaluation of the current state or condition of a sewer system or asset.

Consequence of failure (COF): The impact or severity resulting from the failure of a sewer system or asset.

Criticality: The degree of importance or significance of a sewer conduit or asset in terms of its impact on the overall system.

Defects: Flaws or damages found in sewer infrastructure, including 'line defects' extending along sewer segments and 'point defects'occurring at specific points.

dTabSb.BOR: a document used internally at Sweco which provides guidelines for categorizing and assessing sewer defects based on the general perspective of municipalities.

Factor: In the context of this study, a factor refers to specific elements such as damage to infrastructure, roads, buildings, and the vulnerability of an area, which are analyzed to assess their impact on organizational values affected by sewer collapse.

Geographic Information System (GIS): A system used for storing, managing, analyzing, and visualizing spatial data, which can be utilized in risk-based sewer asset management.

House connections: The pipes that connect individual buildings or properties to the sewer system.

Intervention measures: Categories or levels of actions or interventions based on the condition assessment results. These measures indicate the likelihood of failure and guide decision-making regarding repair, replacement, or further investigation.

Line defect: A defect or damage that extends along the length of a sewer segment.

Manholes: Access points in the sewer system that allow for inspection, cleaning, and maintenance activities.

NEN codes: Codes used in the Netherlands for categorizing and classifying defects in sewer systems.

Organizational value: The core principles and priorities that an organization deems important and stands for, which are used to assess risks. They play a crucial role in determining the significance and impact of risks, as they provide a framework for evaluating the allignment between potential risks and the organization's goals, objectives, and values.

Point defect: A defect or damage that occurs at a specific point within a sewer segment.

Probability of failure (POF): The likelihood or chance that a sewer system or asset will fail or collapse.

Risk assessment: The process of evaluating and analyzing risks associated with sewer failure, including the identification of possible consequences and the likelihood of failure.

Risk matrix: A graphical tool used to assess and prioritize risks based on their probability of occurrence and potential consequences.

Risk-based asset management: An approach to managing assets that incorporates the assessment and prioritization of risks associated with asset failure.

Sewer asset management: The management of sewer systems, including the planning, maintenance, and repair of sewer infrastructure.

Sewer condition assessment: A process or methodology used to evaluate and categorize the condition of sewer systems based on visual inspections or other assessment techniques.

Shapefile: A common geospatial vector data format used for storing and representing geographic features and attributes.

Sinkhole (sewer-related): A depression or cavity in the ground caused by the collapse or subsidence of underlying soil or rock due to sewer infrastructure failure.

Spatial element: A component or feature within a geographic space, such as a buffer, area or object of interest.

Stability loss: A defect in sewer infrastructure that leads to the potential collapse of the sewer and the formation of sinkholes.

Static risk assessment: An assessment of risk based on the current condition and characteristics of the sewer system, without considering dynamic or time-dependent factors.

Survival bias: A bias that occurs when the available data or observations are skewed towards those that have survived or endured until the present, leading to inaccurate estimations or predictions.

Visual inspections: The process of visually examining sewer infrastructure to identify defects, such as displaced joints, pipeline deformation, settled deposits, broken pipes, and intrusions of roots or other objects.

2 INTRODUCTION

This chapter will introduce the topic of the thesis: the implementation of risk-based asset management. Firstly, the importance of sewer asset management is highlighted, followed by its current shortcomings. The relevance of this study in regards to the field of risk-based asset management will be discussed as well as the research its scope and objective. Lastly, the overall structure of the report will be provided.

2.1 RESEARCH CONTEXT

In recent years, asset management has become a more prominent agenda item in the Netherlands (Van der Velde & Hooimeijer, 2010, Tscheikner-Gratl et al., 2019). In 2010, Rijkswaterstaat, an executive agency operating under the Ministry of Infrastructure and Environment in the Netherlands, published a booklet announcing a shift in their operational approach (van der Velde & Hooimeijer, 2010). Rijkswaterstaat is responsible for the construction, management and advancement of the country’s essential national infrastructure networks, which include the national road network, waterway network, and overall national water system (Ministerie van Infrastructuur en Waterstaat, 2023). The booklet stated that the addition of asset management was a fundamental change regarding the work procedure of Rijkswaterstaat (Van der Velde & Hooimeijer, 2010).

Considering wastewater utilities, asset management is defined as the managing of sewer infrastructure capital assets to limit the total costs of operating and owning them while providing the service customers desire (United States Environmental Protection Agency, 2002). Sewer asset management is a necessity considering the major challenge it faces: the need 1) to conform to public expectations regarding the functioning of the infrastructure, 2) for maintenance and rehabilitation due to ageing, and 3) to cope with the changing environment, i.e. climate change, and/or population changes (Tscheikner-Gratl et al., 2019). Additionally, economic reasons play a key role, as sewer infrastructure is associated with excessive costs. In the Netherlands, €800 million is spent every year on replacing and or/rehabilitating 1% of the network. However, it is expected that this percentage

Figure 1. CCTV Pipe inspection (Allpipe, 2020).

should rise to be able to keep up with the ageing sewers to ensure the network keeps functioning adequately (Oosterom & Hermans, 2013).

Sewer inspections form the basis of sewer rehabilitation and replacement strategies. The most common sewer inspection technique is the use of a Closed Circuit Television (CCTV) (Lee et al., 2021, Tscheikner-Gratl et al., 2019). It is a visual inspection technique where images or videos are made of the sewer network, see figure 1. It allows for the identification of defects such as displaced joints, pipeline deformation, settled deposits, broken pipes, and the penetration or intruding of (tree) roots and/or other artificial objects. The visual material is analysed by an expert in a time-consuming stop-and-check manner. Due to its slow nature, only a fraction of the sewer network is inspected annually.

A limitation of the current form of sewer asset management is the neglect of the risk of sewer failure. Risk is defined as a function of the consequence of failure (COF) and the probability of failure (POF). The first step of a risk assessment often entails the identification of possible consequences of a certain event. Consequences of sewer failure can include environmental, social, and economic impacts (Lee et al., 2021). At present, the prioritization of sewer rehabilitation relies exclusively on the assessment of the sewer its condition, which solely reflects the POF. Sewer rehabilitation prioritization is primarily guided by the experiential judgment of a sewer asset manager (J. Roosenstein & J. Houten, personal communication May, 2023). A comprehensive analysis of contextual factors relevant for sewer conduit failure is lacking. Instead, reliance is placed on the localized knowledge of the asset manager to gauge the criticality of a conduit based on its condition and location. This ad hoc approach underscores the need for significant advancements in asset management practices.

2.2 Problem Definition

The present methodology employed in sewer asset management inadequately incorporates the risk associated with sewer failure, leading to suboptimal allocation of resources. The aging sewer systems in the Netherlands require systematic measures for rehabilitation and/or replacement (Stichting RIONED, 2016). Municipalities often face budgetary constraints, and thus need to carefully invest their resources. Moreover, sewer replacement is not only cost-intensive but also disrupts the existing infrastructure, e.g. due to the excavation of roads (Daulat et al., 2022). Striking a balance to minimize costs, societal disruptions, and the potential for accidents arising from sewer failures while ensuring the continued functionality of vital infrastructure is critical. While the probability of sewer collapse may generally be low, the potential damage is not. Sewer failures, specifically sewer collapses, pose a great threat to traffic safety (Kuliczkowska, 2016). Due to their relatively large dimensions and deep installation depths compared to other utility pipes, sewer pipes are inherently more susceptible to sinkhole formations. A sinkhole is a depression or cavity in the ground caused by the collapse or subsidence of underlying soil or rock. In the context of sewer infrastructure, sinkholes can occur when there is a collapse or failure of the sewer system. Sewer collapse can weaken the surrounding soil or rock, leading to the formation of a sinkhole. The pressure and flow of wastewater can exacerbate this process, causing the sinkhole to develop and expand over time. The consequences of these sinkholes can be enormous, particularly when vehicles and individuals fall in, leading to substantial damage, injuries or even fatalities (Kuliczkowaska, 2016). In 2015, there were 1.07 injuries per 1000 km of wastewater sewer resulting from sewer collapses (Stichting RIONED, 2021b). With approximately 97,000 km of foul sewers in the Netherlands (Ministerie van Infrastructuur en Waterstaat, 2021), this equates to around 104 citizens injured due to sewer collapses.

The risk of sewer collapse is escalating over time due to the rising infrastructure age, thereby increasing the POF. The need for a long-term strategy to effectively manage sewer systems is thus essential. However, achieving this poses challenges given the political dynamics of municipalities. Since the local council is renewed every four years, priorities might change within the same time frame (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022). The need for long-term thinking in an environment characterized by short-term perspectives necessitates more strategic planning for sewer rehabilitations. Incorporating a risk assessment can assist in determining the prioritization of sewer conduits for rehabilitation, thereby facilitating a more deliberate replacement strategy (Aberkrom et al., 2016)

2.3 RELEVANCE OF THE RESEARCH

Numerous studies have examined risk-based approaches, which involve assessing the POF and COF of sewer failure (Tscheikner-Gratl et al., 2019; Vladeanu & Matthews, 2019; Baah et al., 2015; Salman & Salem, 2012; Halfawy et al., 2008). Stitching Rioned, the overarching organization responsible for water management research in the Netherlands, has developed a theoretical framework to implement risk-based asset management in the Netherlands (Stichting RIONED, 2018). This framework considers the spatial environment and characteristics of a sewer conduit to assess the risk of sewer failure. The risk of a conduit can inform rehabilitation strategies and future inspection measures. Even though numerous studies on risk-based sewer asset management exist, many of them do not examine the practical implementation aspects. This thesis aims to bridge this gap and create a practical roadmap for the implementation of risk-based asset management.

The use of Geographic Information Systems (GIS) has gained importance in water resources management (Tsihrintzis et al., 1996) and could play a key role in facilitating risk-based sewer asset management as well. GIS is highly effective for storing, displaying, managing, and most importantly analysing spatial data. The use of GIS to evaluate the vulnerability of the geo-spatial environment to sewer failure enables the implementation of risk-based sewer asset management. To evaluate the level of risk, a framework is needed to be able to compare different risks (Aberkrom et al., 2016). A combined risk matrix is an example of such a framework. It uses organizational values, i.e. the core principles and priorities of an organization, to establish the impact and significance of risks. An example of an organizational value is safety, which can be harmed by a lethal accident. The severity of an unwanted event is captured in the combined risk matrix, and combined with the POF to assess the level of risk.

2.4 RESEARCH OBJECTIVE

The purpose of this study is to design a methodology that facilitates the practice of risk-based sewer asset management in the Netherlands. To enable a seamless adaptation, the methodology was maintained to be comprehensible and accessible.

To achieve said objective, the combined risk matrix will be used to establish the level of risk caused by sewer failure. Visual inspections will be used to determine the probability of failure. The consequences of failure will be analysed by performing a buffer analysis i.e., a process where a buffer is generated around an existing geographic feature to identify if certain features fall within the boundary of the buffer (Volusia County Florida., n.d.).

This research will aim to find an answer to:

How can the risk of sewer collapse be determined and what are its implications for sewer asset management?

To provide an answer to this question, a case study on the municipality of Nissewaard will be performed to demonstrate the methodology. The results of the risk analysis will be compared to the most recent analysis performed by Sweco, which is representative of the conventional Dutch approach.

To following questions have been formulated to contribute to meeting the objective of this study:

1. What does sewer asset management entail and how does it compare to risk-based sewer asset management?
2. How can the risk of collapse be assessed using inspection and geospatial data?
3. How does the perspective of the risk of sewer collapse compare to the current sewer condition assessment?

2.5 Research Scope

The research focusses on the risk of sewer collapse, specifically within the Netherlands. A methodology has been designed aiming to provide a valid framework for assessing this risk. The outcomes of the risk assessment will be presented through a map that depicts the identified sewer stability defects along with their corresponding levels of risk. The study primarily concentrates on defects linked to stability loss, which can cause sewer collapse and subsequently give rise to sinkholes. Given its potential for imminent and abrupt failure, stability loss represents the most pressing defect necessitating conduit replacement. The consequences of sewer collapse can be critical, highlighting the urgency associated with addressing stability loss. On the other hand, other failure mechanisms such as loss of water tightness or discharge capacity often lend themselves to remediation through relatively minor interventions like local cleaning or relining. Consequently, the managing of stability defects can be deemed as most critical in sewer asset management. Therefore, the study solely focuses on identifying the risk of stability defects. Some other important limitations inherent to the scope of this research are outlined as follows:

1. The analysis exclusively focuses on the primary conduits, excluding manholes and house connections from consideration.
2. The probability of failure will be determined based on the standardized sewer condition assessment, derived from visual inspections of the sewer system.
3. The case study conducted in Nissewaard will use visual inspection data from the period spanning 2020 to 2023.
4. The research primarily concentrates on consequences that can be investigated using a spatial analysis within a Geographic Information System (GIS) and are relevant to the organizational values reflected in the combined risk matrix of a municipality.

2.6 Internship Background

Sweco is the largest architecture and engineering consultancy firm in Europe (Sweco Nederland, 2023). They work on efficient infrastructure, sustainable buildings and access to clean water and electricity. In the Netherlands, they have multiple divisions dedicated to urban water management, water and wastewater engineering services, water resource planning and the design of flood protection structures. My internship is hosted at the department Water Midden 2, which specialises in pressurised pipelines and sewer asset management.

2.7 Report Structure

The structure of the thesis is depicted in Figure 2, excluding the glossary, bibliography and appendix.

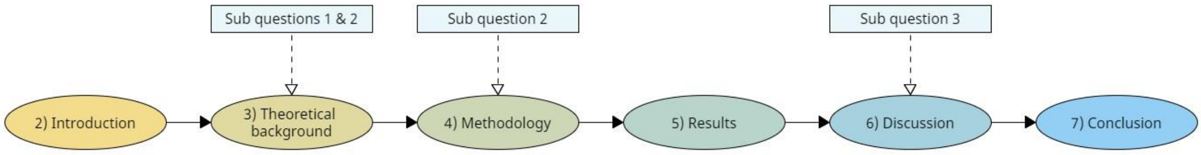

Figure 2. Structure of the thesis.

The next chapter provides the theoretical background of the research. This chapter elaborates on the definition of assets, risk and sewer asset management and compares it to risk-based sewer asset management. In addition, it will provide an overview of existing research on risk-based sewer asset management. The fourth chapter, the methodology, describes the method to assess the risk of sewer collapse. Subsequently, the results of the study will be presented. The discussion discusses the implications of the results for the field of sewer asset management, the limitations of the thesis as well as providing opportunities for future research. Lastly, in chapter 7 the concluding remarks of the thesis will be given.

3 THEORETICAL BACKGROUND

This chapter will provide a theoretical background on asset management and sewer systems. The objective of this chapter is to provide an answer to the first sub-question: *"What does sewer asset management entail and how does it compare to risk-based sewer asset management?"*

This goal will be achieved by defining assets, and asset management and then highlighting its difference from risk-based asset management. Additionally, sewer collapse and its consequences will be described. Lastly, existing methods to determine the risk of sewer collapse are presented, which inform the methodology of this study to give answer to sub-question 2: *"How can the risk of collapse be assessed using inspection and geospatial data?"*

3.1 SEWER SYSTEMS IN THE NETHERLANDS

The sewer system is often taken for granted in countries like the Netherlands (Koninklijk Instituut van Ingenieurs (KIVI), 2009). However, the collection, transport and treatment of wastewater is of vital importance as the risk for diseases caused by contact with faecal bacteria is minimized. The collecting, transporting, and treating of wastewater is also known as sanitation.

About 150 years ago, sewers were used to dispose of the collected wastewater into open water where little harm was expected (Stauffer & Spuhler, n.d.-a; KIVI, 2009). In the beginning, this reduced the nuisance of wastewater, however, it became clear that this method concentrated the problem to the open waters instead. This resulted in the deterioration of local and often even regional water quality (Stauffer & Spuhler, n.d.-a). Currently, this practice of releasing untreated domestic wastewater into the environment has almost completely been eliminated from the Netherlands and has been banned by law (KIVI, 2009).

Most of Dutch sewer systems are combined; both rain- and wastewater are collected and transported in a single pipe together (KIVI, 2009). Thus, both runoff from streets and roofs, as well as wastewater from bathrooms, kitchens and toilets end up in the same sewer system (KIVI, 2009; Stauffer & Spuhler, n.d.-b). The combined sewer system is also called the conventional sewer system (Stauffer & Spuhler, n.d.-b).

Combined sewer systems have combined sewer outflows (CSOs) that serve as emergency outlets as the sewer system is often not able to accommodate the volume of rainwater produced by extreme weather events (Stuart, 2022). It is economically unfeasible to construct a combined sewer that would be capable of accommodating extreme rainfall (KIVI, 2009). Therefore, during extreme rain, when the sewer system is not able to cope with the inflow of water, excess water is discharged into open water (Stuart, 2022; KIVI, 2009). The discharged water is far from clean and a combined sewer outfall event can cause significant damage to the open waters e.g., low oxygen levels causing fish death, the contamination of open water with bacteria hindering recreational purposes, visual pollution, accumulation of persistent materials such as pesticides, and heavy metals that can cause detrimental effects on organisms and biodiversity (Stuart, 2022).

After the acknowledgement of these drawbacks, separate sewer systems were invented (KIVI, 2009). The separate sewer system collects and transports waste- and rainwater separately (Stauffer & Spuhler, n.d.-b; KIVI, 2009). Runoff from roofs and streets is transported via the storm sewer which is a larger rainwater sewer. The wastewater from households ends up in the sanitary sewer, sometimes also called foul sewer. The separate sewer system has the advantage of not discharging diluted wastewater into the environment. Additionally, wastewater treatment plants do not have to treat as much water and can reduce their hydraulic capacity (KIVI, 2009).

The storm drain discharges to open water or is infiltrated into the subsoil (KIVI, 2009). This does not necessarily mean there is no more open water pollution as rainwater, especially in cities, still contains atmospheric deposits, heavy materials, tyre rubbings, fuel, oil, organic material and pesticides that are washed from urban surfaces to end up in the soil or open water bodies (Stauffer & Spuhler, n.d.-b, KIVI, 2009). However, it is still an improvement from discharging black water (wastewater from toilets) in open water.

A weakness of the separate sewer system is the potential of illicit connections, which can either mean wastewater ends up in the storm drain, or vice versa (KIVI, 2009). The discharging of rainwater into the foul sewer can cause a hydraulic overload in the foul sewer resulting in wastewater entering buildings and causing an unpleasant situation. The other way around leads to the direct discharging of wastewater into open water, which defeats the purpose the separate system was designed for. See Figure 3 for a schematic presentation of the combined and separate sewer system.

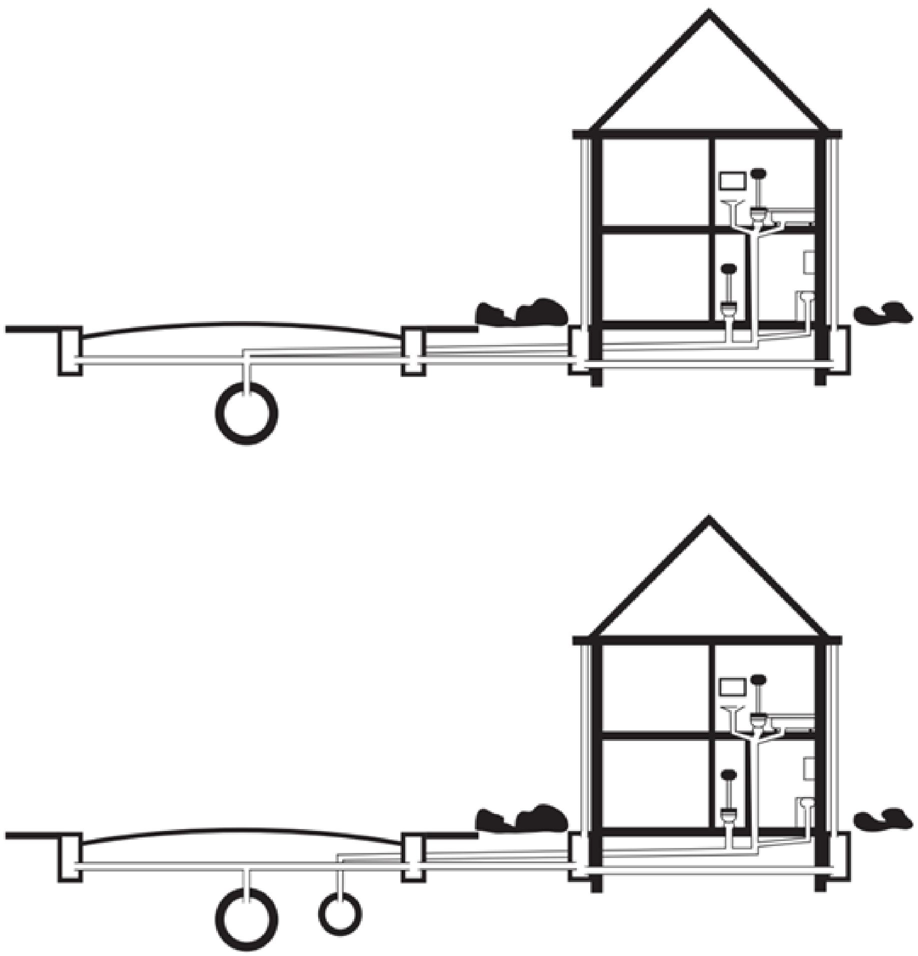

Figure 3. On the top is a schematic of a combined sewer system, which has one main conduit. The bottom image shows a separate sewer system, which has a storm and foul sewer conduit (KIVI, 2009).

To tackle the issues of the separate sewer system, an improved sewer system has been developed. There the rain and wastewater systems are interconnected, often at manholes, where part of the rainwater can be discharged to a wastewater treatment plant to prevent rainwater polluted with wastewater to enter the environment. Then half of the rainfall is treated at the treatment plant to reduce pollution, thereby limiting the advantage of reducing the necessary hydraulic capacity of a treatment plant of the original separate sewer system.

3.2 Sewer Failure Mechanisms

In the Netherlands, sewer failures are often categorized into three groups. Namely the:

- Loss of water tightness;
- Decrease in discharge capacity;
- Loss of stability.

A loss of water tightness in sewer pipes can have various adverse consequences. Firstly, seepage of groundwater into the pipe can lead to the discharge of groundwater, which can damage houses with wooden foundations by exposing the wooden piles to air as the groundwater table lowers, causing pile rot (Urban Green-blue grids & Frankfort, n.d.). Conversely, the seepage of water out of the pipe can contaminate groundwater, posing a significant concern, particularly in areas where drinking water extraction occurs (Reynolds & Barret, 2003).

Secondly, a decrease in the discharge capacity of sewer pipes can result in local flooding, particularly during heavy rainfall when larger volumes of water need to be drained from a neighbourhood. When the sewer system fails to adequately transport water out of the region, it can accumulate on streets and cause flooding (Mekel, 2020).

Lastly, the focus of this report is on the failure mechanism of stability loss in sewer infrastructure, which is associated with the formation of sinkholes. Sinkholes not only have the potential to damage surrounding infrastructure such as roads, pipes, and cables but also pose a safety hazard to individuals, increasing the risk of injuries caused by citizens falling into them (Kuliczkowaska, 2016).

In literature, a distinction is made between structural and hydraulic failure (Ghavami, et al., 2020). The latter relates to a decreasing or increasing flow capacity of pipelines. Whereas structural failure considers a reaction between the pipe its material and its surrounding.

Corrosion and erosion are common types of structural sewer failure (Ghavami et al., 2020). Deformation is another prominent structural defect, which mostly occurs with flexible materials like Polyvinyl Chloride (PVC). Leakages and blockages are regularly occurring hydraulic effects. Leakages cause fluid to seep out of the network or soil to penetrate the pipes. Blockages can be a direct result of this as sediments can block the pipe. In this study, the focus is only on structural failure/loss of stability.

3.3 Sewer Asset Management

3.3.1 Assets

An asset is an object or entity with an actual or potential value to an organization (Stichting Koninklijk Nederlands Normalisatie Instituut, 2014). The value can be tangible or intangible, financial, or non-financial and vary between organization and their stakeholders. The organization bears responsibility for the asset often till the end of its lifetime and sometimes beyond it. Sewer assets entail the system of pipes and structures. Among other things, it includes pipes, conduits, manholes, channels, and pumping stations which are owned by an asset owner, which in the Netherlands is a municipality. In this study, the focus is only on conduits.

3.3.2 Conventional Sewer Asset Management

To comprehend the disparity between current sewer asset management practices and risk-based sewer asset management, it is essential to establish a clear definition of asset management. In essence, asset management encompasses the understanding of an organization's assets and the efficient utilization thereof (Stichting RIONED and STOWA, 2016). It provides a structured approach to asset management based on empirical data while considering future prospects. Implementing asset management entails gaining a comprehensive overview of all assets and their maintenance status, identifying associated risks, and estimating their associated costs. This process typically follows a systematic roadmap encompassing several key stages.

For sewer asset management, the initial steps involve creating a comprehensive inventory of assets on an object basis and categorizing them into distinct networks, thereby enabling the formulation of maintenance strategies (Aberkrom et al., 2016). Analysing the performance levels of each asset provides valuable insights into the overall network performance. Scenarios are developed for each network, outlining various maintenance approaches and their impact on network performance. A risk analysis is conducted to assess the risks associated with different performance levels based on the formulated maintenance strategies. Furthermore, a long-term cost analysis, often known as Life Cycle Costing, is performed for each maintenance strategy, accounting for the entire lifespan of an asset, including initial investment, management and maintenance costs, and demolition expenses.

The scenarios are then presented to the client, empowering them to make well-informed decisions. Once a maintenance strategy/scenario is selected, the necessary tasks are assigned, and appropriate parties are enlisted to carry out the required work (Aberkrom et al., 2016).

Summarizing, sewer asset management encompasses a structured workflow that offers insight into the current status of all assets and provides effective management strategies. It aims to avoid unexpected surprises while maintaining flexibility in potential strategies and ensuring transparency regarding outcomes, costs, and risks.

In the context of sewer asset management, the assets primarily include pipes, conduits, manholes, and pumping stations. Figure 4 illustrates the current workflow of sewer asset management (adapted from Aberkrom et al., 2016).

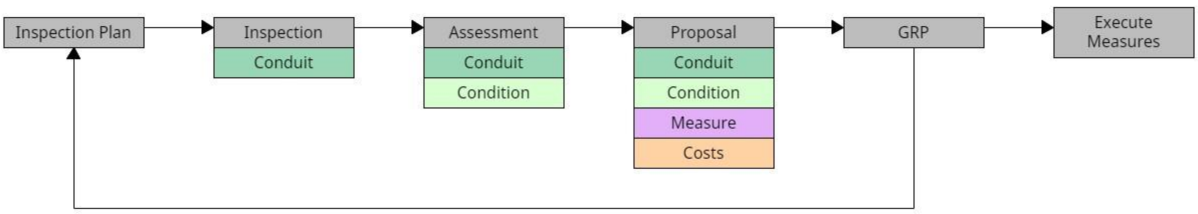

Figure 4. Current sewer asset management workflow adapted from Aberkrom et al., (2016)

The process commences with the development of an inspection plan to accomplish the initial steps of creating an asset overview and assessing their condition. Subsequently, a proposal is formulated, encompassing the conduit, its condition, proposed measures, and associated costs. These plans are integrated into the Municipal Sewer Plan (GRP), which outlines the municipality's approach. Ultimately, the plans influence the new inspection strategy, and the proposed measures are implemented.

The GRP encompasses a plan outlining how the municipality intends to fulfil its statutory water-related responsibilities (Kenniscentrum InfoMil, n.d.) These duties encompass the collection and conveyance of urban wastewater, management of stormwater runoff, and mitigation of adverse effects related to the groundwater table. The GRP is a legally mandated document until 2024, as stipulated by the Law of Environmental Management (Wet millieubeheer). Typically, a GRP has a planning period of four years and is developed in collaboration with various stakeholders involved in the water cycle, including provincial authorities, surface water managers, and wastewater treatment plant operators.

3.3.3 Risk-Based Asset Management

3.3.3.1 Definition of Risk

The nature of risk is inherently complex, and includes various dimensions that are crucial to its understanding and assessment. Risk can be defined as the potential for an event or circumstance to result in adverse consequences or undesirable outcomes. It involves uncertainty and the possibility of harm, loss, or negative impacts on objectives, assets, or individuals (Etti et al., 2006). In short, risk is a function of both the probability of failure (POF) and consequence of failure (COF) (Baah et al., 2015; Vladeanu & Matthews, 2019, Salman & Salem, 2012).

The probability of failure represents the chance that an adverse event or outcome will occur. The probability of failure is often associated with a level of uncertainty. The consequence of failure can include various dimensions, such as financial losses, reputational damage, environmental impacts, human health and safety hazards, and social disruptions (Salman & Salem, 2012; Vladeanu & Matthews, 2019).

The probability of an undesired event is often expressed as a chance per unit of time, e.g., once per 10 years. The consequences of an unwanted event can include socio-economic and environmental impacts which are mostly expressed qualitatively (Lee et al., 2021; Salman & Salem, 2012; Vladeanu & Matthews, 2019). Other approaches entail expressing the consequences in a monetary unit (Korving et al., 2003; Martin et al., 2007).

Qualitative approaches often use terms such as extremely low, moderate, high, and extremely high to describe the severity of consequences. The risk of a sewer pipe failure can be determined by performing a multiplication if consequences are expressed in monetary terms. If a qualitative assessment of the COF is used, a risk matrix is more appropriate (Vladeanu & Matthews, 2019; Salman & Salem, 2012).

It is important to note that risk is not static, but evolves over time (Etti et al., 2006). Temporal and spatial changes can lead to a change in risk. Most risk assessments are static, and capture risk based on a fixes set of parameters and assumptions, providing a snapshot of risk at a specific point in time (Kristamuljana et al., 2018). In contrast, dynamic risk models acknowledge the dynamic nature of risk by incorporating changing variables, evolving circumstances and the interplay of various factors over time. Dynamic risk models theoretically provide a more nuanced and realistic representation of the evolving risk landscape. However, since dynamic risks are difficult to predict as they depend on a variety of external factors that are difficult to anticipate or measure, dynamic risk models are not commonly used yet (Etti et al., 2006; Kristamuljana et al., 2018).

3.3.3.2 Risk-Based Asset Management in the Netherlands

Risk-based asset management distinguishes itself from conventional asset management by incorporating spatial context, as highlighted by Aberkrom et al. (2016). This integration allows for the implementation of a comprehensive risk analysis, which yields valuable insights into failure types, causes, effects, and mechanisms. Consequently, this information can be used to plan future inspections and maintenance. The risk level assigned to a pipeline serves as a prioritization criterion when multiple pipelines require replacement. This prioritization factor, alongside cost considerations, plays a crucial role in decision-making regarding replacement strategies.

As depicted in Figure 5, the assessment of risk extends beyond the condition of the segment. The inspection plan is informed by a risk matrix, which serves as a framework for comparing and evaluating different risks. Developing a risk matrix entails establishing the vision and mission of the organization and incorporating them into a combined risk matrix. This matrix represents the organization's norms, values, and their respective relative importance. Examples of organizational values are to care for environment, finance, and safety. Each organizational value is associated with corresponding risks, each carrying its level of criticality. The combination of probability and consequences per organizational value is represented in the risk matrix. For an illustrative example of a business value risk matrix, refer to Figure 6.

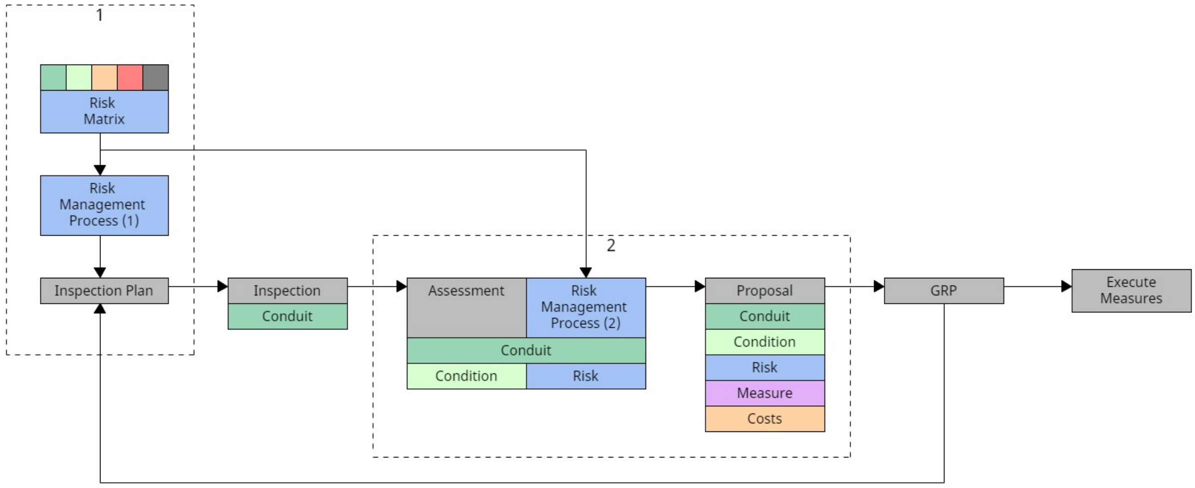

Figure 5. Workflow of risk-based asset management (adapted from Aberkrom et al., 2016)

Consequences									
Severity						Likelihood			
Rating		People	Environment	Assets	Reputation	1 Remote	2 Unlikely	3 Likely	4 Frequent
						Has occurred in E&P industry	Has occurred in company	Has occurred several times/year in company	Has ocurred several times/year in asset area
1	Minimal	Slight injury or health effects (inluding first-aid cases) not affecting work performance or causing disability.	Minor envionmental damage; effects confined to lease.	Negligible production loss; production and/or equipment loss < \$100k	Localized concerns; no media attention; minimal public impact.	1	2	3	4
2	Moderate	Medical aid injury; restricted work; evacuation of jobsite.	Moderate environmental damage; widespread impacts to land, water, air.	Short-term (< 1 week) facility/equipment outage; production and equipment loss >\$100k.	Company-wide attention; brief local area attention; regulatory action resulting in administrative response.	2	4	6	8
3	Serious	Lost time injury; short term health impact; evacuation of facility and surrounding area.	Severe but reversible or short-term environmental damage; widespread impacts to land, water, air.	One week facility/ equipment outage; production and equipment loss >\$1M.	Prolonged local area attention; brief operating region attention; regulatory action resulting in fines or punitive action.	3	6	9	12
4	Major	Fatality; multiple injuries; long-term health impact; permanent disability; evacuation of facility and community.	Severe irreversible or long-term environmental damage; widespread impacts to sensitive environments and/or major water bodies and/or air.	One month or more facility/equipment outage; production and equipment loss >\$10M.	Widespread concerns with extensive adverse media coverage; prolonged operating region attention; action resulting in legal prosecution or suspension of operations.	4	8	12	16

RISK LEVEL=>	SERIOUS Stop activities unless risk controls have been implemented and the risk is reduced to a lower level.	HIGH Implement extensive risk reducing measures.	MODERATE Implement risk mitigation measures.	LOW Manage for continuous improvement.
APPROVAL TO PROCEED =>	Asset Team Manager	Operations Manager	Superintendent	Supervisor

Figure 6. Example of a combined risk matrix created for the International Association of Oil and Gas Producers. , with the organizational values on the left and the risk matrix on the right. (Pinheiro et al., 2011).

3.3.4 Risk-Based Asset Management in Scientific Research

Multiple studies have created a methodology to assess a pipe segment its risk of failure. The objective of these studies is often to develop the capability to prioritize future inspection of uninspected pipes (Ghavami et al., 2020; Lee et al., 2021; Salman & Salem, 2012). Other studies also study the use of risk for prioritising sewer rehabilitation and interventions (Baah et al., 2015; Shahata et al., 2022; Ward & Saviç, 2012; Venigalla & Baik, 2007; Vladeanu & Matthews, 2019; Hintz et al., 2007). Commonly, the level of risk is determined in two steps, firstly the probability or likelihood of failure is determined (POF), and secondly, the consequence of failure is determined (COF). There are then several methods to combine these factors, of which the most used method is the usage of a risk matrix as shown above.

The POF can be determined in a variety of ways. Many studies make use of statistical models which make use of future condition ratings by looking at the historical pipe condition data which have been obtained by pipe inspection. Widely used models include regression methods, artificial neural networks, survival functions, Markov chain Models, Bayesian networks and other optimisation tools (Vladeanu & Matthews, 2019; Ghavami et al., 2020; Lee et al., 2021; Shahata et al., 2022; Ward & Saviç, 2012; Salman & Salem; Halfawy et al., 2008). These models often include information on the age, length, diameter, depth, material, slope, soil type and number of failures to predict the future condition rating. The study by Baah et al., (2015) makes use of closed-circuit television (CCTV) technology, where structural and operational defects were given a severity score for the inspected pipes, whilst making use of a random forest data mining tool to predict the condition of uninspected segments. According to Tscheikner-Gratl et al., (2019) CCTV inspection techniques are most dominant in determining the condition and operability assessment of sewer systems. A more in-depth analysis of the manners to determine the POF is given in section 3.3.4.1. Probability of sewer failure.

The COF assessment varies slightly between studies, some express the COF using a score, others in a financial loss. The factors which are considered to determine the effect of failure vary per study. Halfawy et al. published a paper in 2008 with a methodology to improve sewer rehabilitation prioritization schemes. In their approach, sewer pipe characteristics and above-ground facilities are considered to determine the impact of sewer failure. Elements like the diameter, burial depth and sewer type were considered as well as the adjacency to railways, waterways and roads. This study has been referenced by multiple papers that too aimed to create an improved methodology for sewer rehabilitation or inspection schemes (Salman & Salem, 2012; Baah et al., 2015, Vladeanu & Matthews, 2019, Tscheikner-Gratl et al., 2019; Ghavami et al., 2020, Lee et al., 2021)

In these more recent studies, there is a distinctive focus on making use of the Triple Bottom Line (TBL), which entails that the COF does not only include the immediate economic perspective but also the environmental and social perspective (Vladeanu & Matthews, 2019; Lee et al., 2021). The TBL approach includes multiple impact factors caused by a possible sewer segment failure with a distinction made between economic damage, e.g., costs caused by the utility, environmental damage, e.g. contamination of groundwater, and social impact which includes travel delays, property damage and service outage. The impact factor is sometimes scored qualitative with having a low, moderate or high impact, other methods make use of impact ratings using a score, e.g. between 1-5. According to Vladeanu et al., (2019), not many studies have documented the use of TBL strategies as social and environmental impacts are difficult to quantify as costs can be indirect or intangible.

The impact ratings are often established by multiplying a rating and a weight for a certain criterion. The most recent studies make use of the Analytic Hierarchy Process (AHP) to establish a weight for each criterion (Ghavami et al., 2020; Lee et al., 2021; Vladeanu & Matthews, 2019). Older studies used other methods, e.g., a decision maker could directly assign a weight to a certain criterion (Halfawy et al., 2008), or a weighted decision matrix was used instead (Salman & Salem, 2012; Baah et al., 2015). The Analytic Hierarchy Process (AHP) involves creating a pairwise comparison matrix to assess the relative importance of factors (Ghavami et al., 2020; Vladeanu & Matthews, 2019). In this matrix, an expert assigns scores between 1 and 9 to indicate the importance of one criterion compared to another. A score of 9 signifies extreme importance, while 1 represents equal importance. Values between 0 and 1 denote lesser importance, with 1/9 indicating minimal significance. The matrix captures the comparisons between criteria, with values above 1 indicating one criterion’s greater importance over another. The reciprocal values appear in the corresponding positions, and the diagonal of the matrix contains 1. By computing the normalized right eigenvalue and principal eigenvalue for each matrix, the relative importance weights of each criterion can be determined.

If the weight of each impact factor is determined, sub-criteria are formulated that attribute a certain score or rating if a conditional is met (Ghavami et al., 2020; Vladeanu & Matthews, 2019; Ward & Saviç,2013; Salman & Salem, 2012; Baah et al., 2015). For example, if a pipe is between 0 and 10 years old, a rating of 1 might be attributed, whilst for pipes older than 50 years a rating of 5 might be attributed. For each impact factor conditionals are created that attribute a rating, this rating can then be multiplied with its relative weight. The summation of all criteria and their respective rating and weight over a pipe segment represent its total consequence of failure.

Depending on the impact factors and their sub-criteria a geographic analysis is performed. As stated before, some studies only make use of pipe characteristics like age, soil type and depth, whilst others also consider the nearness of geographical features such as roads, waterways and other types of infrastructure. For these types of criteria, a buffer analysis is often used, where depending on the distance of a geographic element to the pipe a rating is assigned. More information on how different studies approach determining the COF is given in section 3.3.4.2.1 Determination of consequences of sewer failure.

After both the POF and COF are determined, the risk of each pipe segment can be assessed. In many studies, the COF and POF are entered into a risk matrix where the COF On the X-axes and the POF on the Y-axes to attribute a risk level to a sewer segment (Salman & Salem, 2012; Lee et al., 2021; Baah et al., 2015). Another strategy is to multiply the COF and POF and group values together at a certain level of risk (Ghavami et al., 2020; Shahata et al., 2022; Salem & Salman, 2012).

3.3.4.1 Probability of Sewer Failure

The probability of sewer failure is an important parameter for understanding the risk of sewer failure. Often, when the failure probability is high, replacement or renovation of conduits is recommended. The condition of the sewer network is commonly determined by visual inspections in the Netherlands (Stichting RIONED, 2020b). Pipelines are usually inspected after 30 years of service and are then repeated every 10 years or so (Personal Communication J. Roosenstein, 2023). During an inspection, the visible defects are noted as well as their defining characteristics. The inspection data is then analysed and given a class of severity, using the report of Stichting RIONED: "Classificatiemethdoeik van visuele inspecties", which bases itself on the NEN-EN 13508-2:2003+A1:2011 (Stichting RIONED, n.d.-a; Verkerk, 2019). The level of severity is denoted using a number between 1-5, where a score of 5 is the highest severity level (Stichting RIONED, n.d.-a).

In the U.S., another system is applied where they make use of a standardized sewer assessment protocol. This protocol is developed in the United States by the National Association of Sewer Service Companies (NASSCO) and is called the Pipeline Assessment Certification Program (PACP) (NASSCO, 2021). The standardized sewer assessment protocol entails the use of a scoring system where the sewer its condition is expressed in a score from one to five, called the defect grade. This grade corresponds to a certain rate of deterioration as a proxy for its condition. For example, a defect score of five entails the need for immediate action based on the estimation the pipe will fail within the next five years, see Table 1. The study by Koo & Ariaratnam (2006) applied the standardized NASSCO assessment to determine the failure probability of a sewer segment. The overall rating of a sewer pipe was determined by performing a simplified version of the Quick Rating method: a methodology to calculate the overall pipe rating by multiplying the defect score by the times a certain defect score is found in the pipe and summing all these values. The simplified version entailed only using the worst defect grade as representative for the entire pipe, supported by the philosophy a sewer pipe its quality is as good as its worst condition.

Table 1. NASSCO Defect Grades (Koo & Ariaratnam, 2006)

Defect grade	Defect condition	Description	Rate of deterioration
5	Immediate attention	Defects requiring immediate attention	The pipe has failed or will likely fail within the next 5 years
4	Poor	Severe defects that will become grade 5 defects within the foreseeable future	The pipe will probably fail in 5 to 10 years
3	Fair	Moderate defects that will continue to deteriorate	Pipe may fail in 10 to 20 years
2	Good	Defects that have not begun to deteriorate	The pipe is unlikely to fail for at least 20 years
1	Excellent	Minor defects	Failure is unlikely in the foreseeable future

However, as the upkeeping of the database with the maintenance information and inspection history of sewer pipes is costly, many studies have attempted to find a way around using inspection data and have instead opted for a model that predicts the deterioration level of sewer pipes make use of only general information (e.g., diameter, location, length) (Marlow et al., 2007). At the start of developing sewer deterioration models, studies were often inspired by deterioration models of pavements and bridges (Baik et al., 2006; Ariaratnam et al., 2001).

According to Ana and Bauwens (2010), there is a distinction to be made between three types of sewer deterioration models: statistical, artificial intelligence-based and physical models. Statistical models are among the most widely used in estimating the condition of sewer segments (2010). The most used method is the general linear regression model, which has been used, among others, by Salman and Salem (2012) who applied three types of regression models: ordinal regression, binary logistic regression and multinomial logistic regression. Other widely used statistical models include a logistic regression model. Ariaratnam et al., (2001) too adopted this methodology and was one of the first studies to apply it for predicting the sewer condition. The model its input consisted of CCTV inspection data, then using 5 basic deterioration factors, namely the age, diameter, sewer type, depth and material of a sewer segment the effect on the occurrence of structural sewer defects was analysed. Other studies that applied logistic regression include Chughtai and Zayed (2008) and Angarita et al., (2017). The regression model is known to be well-suited for the identification of basic relationships of variables that influence the condition of a pipe segment. They are often easy to understand as the deterioration factors are directly correlated to the condition of a sewer pipe (Ana & Bauwens, 2010). A limitation of using linear logistic regression models is the requirement for a linear relationship between the independent and dependent variables (Salman, 2010).

To explore the impact of a multitude of attributes on the likelihood of a defect occurrence, Montoya (2019) applied survival analysis. The study considered the material, sewer type, diameter, shape and length. Another statistical method includes the use of the (fuzzy) Markov chain method (Baik et al., 2006), of which the studies by Wirahadikusumah et al. 2001, Micevski et al., 2002 and Kleiner et al., 2001) belonged to the first studies that applied deterioration models for estimating the condition of sewers. Additionally, stochastic models (Le Gat, 2008) and Bayesian networks (Anbari et al., 2017; Madadgar & Moradkhani, 2014) also belong to statistical models applied for sewer deterioration modelling.

Artificial neural networks, which are intelligence-based models, make use of a "black box" approach and perform better in successfully predicting the condition of a pipe (Ana & Bauwens, 2010). Tran et al., (2007) made use of two artificial neural networks that consider physical factors (e.g. diameter, slope, depth, age) as well as environmental factors (soil type) as input data and studied the performance of both models. Other intelligence-based models include the use of a decision tree model, machine learning techniques (Syachrani et al., 2013), and random forest models (Harvey and McBean, 2014; Lee et al., 2021). Harvey and McBean were the first to use a random forest data mining tool where the input consisted of an inspection dataset with defects classified in terms of severity using the Water Research Center Manual of Sewer Condition Classification. This manual is the basis of the NASSCO defect grades as described above (Vanier & Rahman, 2004). The Canadian organization: North American Association of Pipeline Inspectors (NAAPI), uses this manual as well. The study of Baah et al., (2015) then used the same model as Harvey & McBean to establish the risk of sanitary sewer pipe failure in Ontario. Lee et al., (2021) is one of the most recent studies making use of the random forest methodology, which is a commonly-used machine learning algorithm suitable for classification and regression. The use of machine learning allows one to find non-linear relationships; however, an extensive database is required to find these relationships.

Sewer deterioration models have one thing in common; the use of predictive variables to determine the condition of a sewer pipe, which often includes the age, depth, length, diameter, slope, soil type and number of failures of a pipe. A predictive variable is a variable used to predict a future scenario based on given circumstances. A serious limitation of sewer deterioration models is that they are based on available inspection data which are subject to survival bias (Tscheikner-Gratl et al., 2019). As only pipes that have survived until the inspection are present in the inspection database, models are expected to underestimate the actual condition of a sewer segment. Conduits that are in a very poor state are often replaced before they are broken, therefore it is unknown how long such a pipe would have lasted if it would not have been replaced. This causes an overestimation of the duration of the lifespan of pipes, as only the very old pipes that are still in a good enough state are around to be inspected, and thus in the dataset, while bad pipes have been removed already and are not part of the database. This also causes an underestimation of sewer segments to be in a poor state. According to Tscheikner-Gratl et al., (2019), there is no apparent best modelling approach, however, it seems that machine learning models outperform statistical models. Currently, deteriorating models are often evaluated by assessing the True Positive Rate (TPR); Observed in poor condition pipes that were correctly labelled as beings in a poor condition by the model, False Positive Rate (FPR), i.e. the percentage of pipes wrongly predicted in a poor condition and the PPV; the Positive Predictive value, which entails the percentage of pipes that were predicted to be in poor condition and later after observation were actually in poor condition. The average TPR is 64% and the PPV is 57% (Tscheikner-Gratl et al., 2019).

3.3.4.2 Consequences of Sewer Failure

The risk of sewer collapse is mainly dependent on its location since the consequences of sewer failure are directly related to the exposed environment. For example, a sinkhole could damage above and underground infrastructure. Other consequences of sewer collapse include, but are not limited to, traffic obstruction, accidents, social impact (e.g. resignation of politicians or negative publicity), damage to buildings, and health impact (e.g. accidents) (Mekel, 2020). This study only considers consequences mentioned in the combined risk matrix of a municipality.

3.3.4.2.1 Determination of Consequences of Sewer Failure

The consequences of failure are often determined by looking at the economic, environmental and social impact. However, how this impact is quantified differs. Vladeanu & Matthews (2019) applied the aforementioned approach and divided consequences into these three categories, where EC represent economic costs, SC social costs and ENV environmental costs. Together they represented the total consequence of sewer failure. To determine the SC, EC and ENV they attributed a rating of 1-5, where a factor, e.g. age of pipe, has an attribute (conditional statement, e.g. <10 years, between 10 and 25 years, etc) that is linked to a certain rating. A rating was used instead of a quantitative value as factors were often not quantifiable in the same units, making them hard to compare. For example, the economic costs included the pipe its age, diameter, length, depth, accessibility, distance to critical laterals, soil type and seismic zone. These factors are all measured in a different unit, e.g., years, meters or a category. For soil type, the categories include and are between, low corrosiveness and highly corrosive.

These ratings are then multiplied by a weight that came about using AHP. The summation of all ratings of each factor for a pipe multiplied with their respective weight then represents the total COF of a sewer pipe, where a score of 5 is seen as a high-impact consequence.

A very similar approach was carried out two years later by Lee et al., (2021), where the only difference where the exact factors used, the three categories were the same. However, most factors were expressed as the nearness of a certain object or entity, e.g. the nearness of a river, railway, medical centre or forest.

Salman & Salem (2012), use a slightly different approach, as instead of a rating, a performance value is attributed. Similarly, for each factor conditional statements are developed to assign a performance value, which is between 0-100, where 100 represents the greatest possible impact. They divided the factors into two groups: qualitative and quantitative characteristics of the sewer pipe. The latter considered proximity to the nearest building, depth, number of building lateral connections, proximity to rivers and streams, size, and number of complaints. The qualitative group consisted of roadway type (e.g., interstate, collector road, local street), located under railroad track (yes or no), the function of the pipe section (interceptor, trunk, local collection pipe), etc. The consequences of failure were calculated by summing all weights multiplied by their performance value scores for all factors for a sewer conduit.

Baah et al. (2015) and Lee et al. (2021) used impact factors to assess proximity and other characteristics of objects. These factors included pipe diameter, depth, presence of a railway track, downtown location, proximity to hospitals, schools, buildings, rivers, parks, stormwater pipes, and roadway type. Each impact factor had sub-criteria with assigned performance values, which were then weighted using the Analytic Hierarchy Process (AHP). This approach was expanded upon by Ghavami et al. (2020), which used spatial elements and buffer analysis to establish the COF. The severity of consequences was categorized as none, low, medium, or high, and different zones were outlined using buffers. Scores were assigned based on the categorization of pipes within multiple (risk) zones.

Besides qualitatively assessing the consequences, the study of Korving et al., (2003) estimated the expected costs of damage from CSO spills in monetary terms to prioritize sewer rehabilitation, in particular upsizing the sewer. By estimating the (environmental) costs of CSO spills and comparing this to the costs of increasing the storage space in the sewer, prioritisation to upsizing sewers could be given. Martin et al., (2007) also expressed the consequences of failure as the risk costs associated with failure for each sewer pipe. The costs were calculated by a model, which considered information about each pipe, e.g. the elevation, material type, installation date, and proximity to geologic and structural features to attribute financial consequences, including both direct and indirect (social and environmental) costs. For example, in the model, a pipe located under a building was given a multiplier based on added costs of repairing due to the relative inaccessibility of the pipe.

To summarize, most commonly sewer risk assessments include the use of a quantitative score to determine the COF. This score comes about by making use of factors and sub-criteria to assign a score. To make a distinction between the relevance of factors, a weight is attributed to a factor using the input of field experts.

4 METHODOLOGY

This chapter aims to provide an answer to the sub-question: "How can the risk of sewer collapse be assessed using inspection and geospatial data?". The methodology to determine the level of risk of sewer collapse will be described. Then the case study location will be characterized. Followed by a description of how the key components of risk: the probability and consequence of sewer collapse were assessed. Additionally, the replacement strategies associated with both current and risk-based asset management are discussed. Lastly, the tools and materials used in the thesis are presented.

4.1 DETERMINATION OF RISK

The level of risk was determined using a combined risk matrix, which is a framework that ranks issues according to their significance (Aberkrom et al.,2016). It is commonly applied for accidents. It can be used as a screening tool to provide guidance on which issues need to be tackled first.

A combined risk matrix can contain exposure to diverse types of accidents, e.g., damage to the environment, harm to humans, financial loss, or impact on public image. If these losses can be expressed in a common term, for example, financial loss, a single matrix can cover all issues together (The Safety Artisan, n.d.).

The combined risk matrix contains a "risk space" which is characterized by the two components of risk namely consequence on one axis and likelihood on the other (Baah et al., 2015; The Safety Artisan, n.d.). The axes cover the full range of outcomes, where each range is divided into several categories to outline the cells of the matrix.

The categories on the two axes can be expressed in fully quantitative, semi-quantitative or purely qualitatively (Baah et al., 2015; The Safety Artisan, n.d.). For example, where:

- Qualitative:
  - Likelihood is small/probable/great
  - Severity is minor/moderate/catastrophic
- Semi-quantitative:
  - Likelihood is e.g., likely to occur twice per year
  - Severity is e.g., a single fatality
- Quantitative:
  - Likelihood is e.g., 10^{-4} per year on one site
  - Severity is e.g., between 1.0-5.0 weighted injuries and fatalities

Every cell in the matrix is appointed an indicator to represent the relative importance of accidents falling in that zone (based on likelihood and consequence). An indicator could be a risk descriptor (e.g., low, high), risk score (e.g., a number from 1-5), priority category (high, medium, low), risk class (A-D), a measure (monitor, mitigate impact, etc), or expired loss (e.g., €30.000 per year)

The use of a risk matrix allows one to systematically rank various events on a comparative basis (Baah et al., 2015). The risk of failure for different system components, in this case, the collapse of sewer conduits, can directly be compared with each other. Thus, opening the possibility to invest in those defects where risk can be maximally reduced for a given investment.

The methodology has been designed around the use of a semi-quantitative risk matrix. The advantage of using the risk matrix to determine the level of risk is its flexible and scalable nature, it can cover different impacts that are of importance to the municipality. The next section will describe the municipality that has been used as a case study and the risk matrix used to determine the level of risk for sewer collapse.

4.1.1 Case Study Characterisation

Nissewaard is a municipality in the South of the province Zuid-Holland (South-Holland) (Wikipedia-contributors, 2023), see Figures 7 and 8. It is situated on the island Voorne-Putten. The municipality is a combination of the former municipalities Spijkenisse and Bernisse. Nissewaard has around ninety thousand inhabitants and an area of 98.82 km2, of which 16,49 km2 is surface water (Centraal Bureau voor de Statistiek, n.d.; Wikipedia-contributors, 2023).

Within Nissewaard, the following cities are situated: Abbenbroek, Heenvleit, Tweede Vlotbrug, Zuidland, Geervliet, Biert, Hekelingen, Simonshaven, Beerenplaat and Spijkenisse, which is the largest city in Nissewaard.

Since the sixties, Spijkenisse started growing from a small village with 2500 inhabitants to the large city it currently is (Bewonersgroep Waterland, n.d.). Due to its location with respect to the ever-growing Rotterdam Ports, many employees of the port settled in Spijkenisse to live closer to their job. In the sixties, the neighbourhoods Spijkenisse Noord, Sterrenkwartier and Groenewoud were built and at a fast tempo, the village grew to an inhabitant number of 30.000 at the end of the 70s, which is when the neighbourhood Waterland was finished. In the 80s Spijkenisse is appointed a “groeikern” by the central government. This meant Spijkenisse had to develop itself as a growing residential area that offered affordable social housing. The inhabitant number climbed to 70.000, where most new inhabitants settled in the neighbourhoods of Vriesland, De Hoek and Vogelenzang. After the obliged development time had passed, the more expensive residential areas, Schenkel and Maaswijk, were built. The most recent developments are repurposed industrial areas for residential areas in Centrum-Staalmeesters and Vierambachten. Additionally, space has been cleared for luxurious housing in the village of Hekelingen and Maaswijk Landgoed. Lastly, there is a completely new neighbourhood built beside the river Meuse called the Elementen. All these projects were developed to attract middle- and upper-class incomes to move towards Spijkenisse. Overall, Nissewaard has differently aged sewer pipes due to its growing nature.

The distribution of the inspected sewer conduit its age, material and diameter are shown in Figure 9-11.

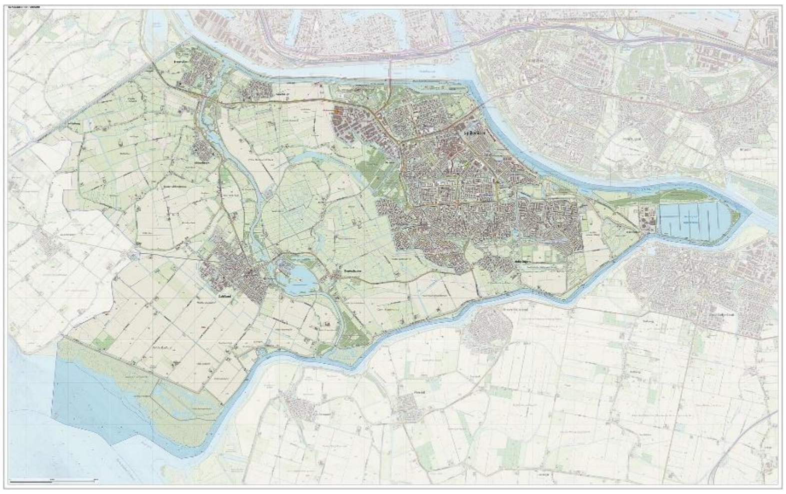

Figure 7. Municipality Nissewaard (Van Aalst, 2022)

Figure 8. Location of Nissewaard within the Netherlands (Centraal Bureau voor de Statistiek, 2016)

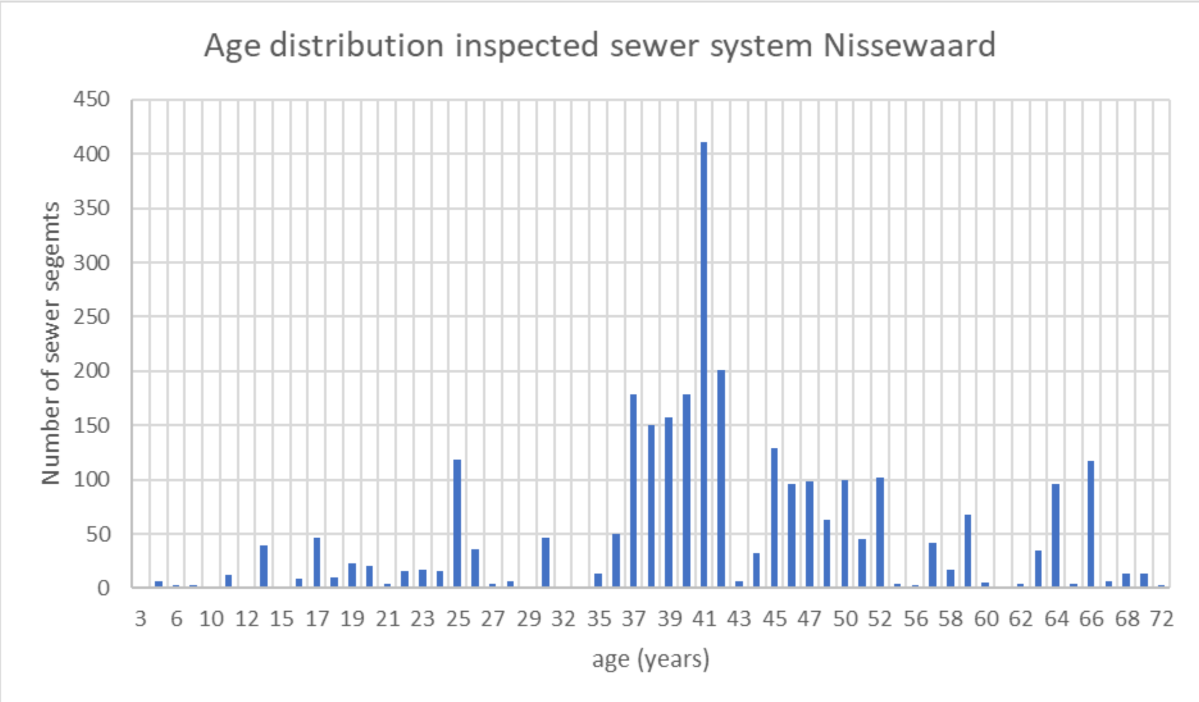

Figure 9. Age distribution of inspected sewer conduits in Nissewaard.

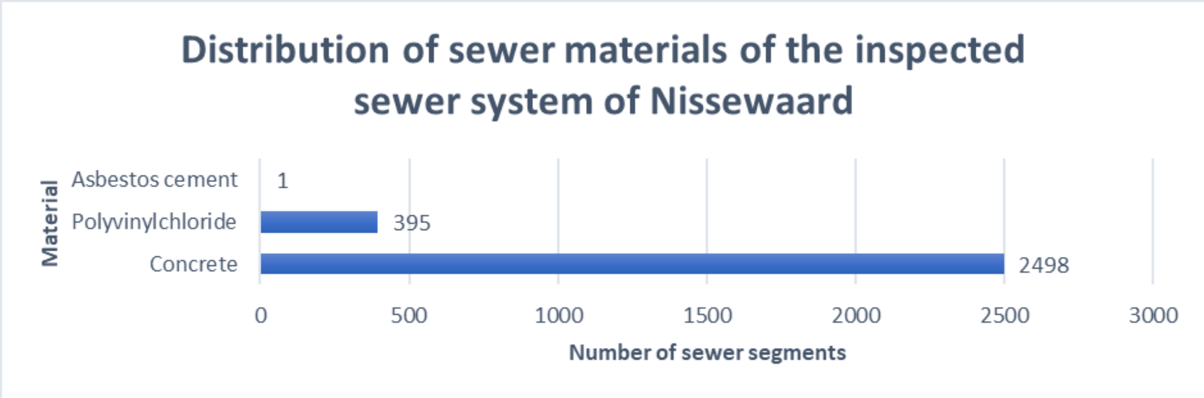

Figure 10. Material distribution of inspected sewer conduits in Nissewaard.

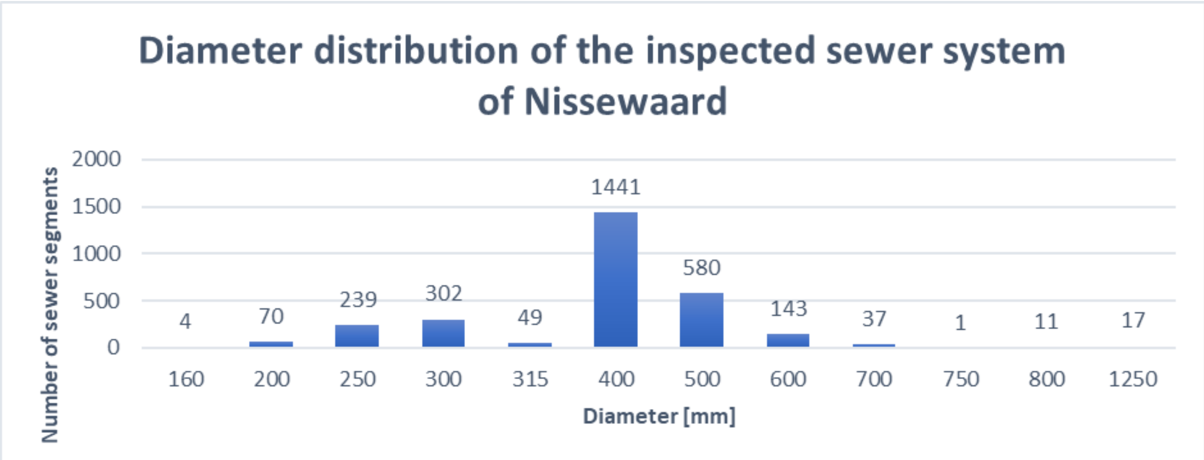

Figure 11. Diameter distribution of inspected sewer conduits in Nissewaard.

4.1.1.1 Risk Matrix Nissewaard

To determine the level of sewer collapse in Nissewaard, the risk matrix of Dordrecht as shown in Table 2 will be used. Nissewaard does not have a risk matrix and it is assumed the matrix of Dordrecht is representative of the municipality of Nissewaard. Dordrecht is a town that is located in the South of Holland, with 121.449 inhabitants (Centraal Bureau voor de Statistiek, n.d.). Its comparable size and locations allow for the use of Dordrecht its risk matrix for Nissewaard.

The risk matrix is slightly altered, as the risk matrix had one additional organization value: noise and vibration. The risk matrix of Dordrecht is namely applicable for the entire municipality, thus not all values are as applicable. Therefore, noise and nuisance are not considered for the risk of sewer collapse as it is 1) irrelevant to sewer collapse and 2) could not be studied using a geospatial analysis and thus not fit the scope.

4.2 Determination of Probability of Structural Sewer Failure

The research explored the feasibility of utilizing a sewer deterioration model developed by Lopez et al. (in press) as a means to estimate the probability of sewer collapse. However, the application of this model was hindered by several limitations. Firstly, it was observed that the relationship between sewer defects and conduit characteristics differed significantly across different locations, highlighting the need for a location-specific model. Unfortunately, the creation of such a model specific to the study area of Nissewaard was not feasible within the scope of this thesis. Although a substitute model developed for a similar municipality, such as Almere, could have been considered, the dissimilarities in size, population, and age of the sewer systems between Nissewaard and Almere would have posed substantial challenges in terms of accuracy and reliability in predicting sewer failure probability.

Furthermore, the Bayesian network model employed by Lopez et al. (in press) suffered from survival bias, which led to an overestimation of the remaining lifespan of sewer conduits. Additionally, the lack of data on actual sewer collapse events limited the model's ability to accurately predict such occurrences. These limitations underscored the need to explore alternative approaches to assess the probability of sewer failure.

Acknowledging the shortcomings of using visual inspections to determine the probability of failure (POF), this study recognized the subjectivity and bias associated with inspector interpretations. However, it should be noted that deterioration models, including the Bayesian network model, also rely on subjective input, and therefore do not necessarily resolve the issue of subjectivity. In contrast, the sewer condition assessment, despite its limitations, offers some advantages. Notably, it does not suffer from survival bias since the inspection data is solely used to assess the condition of the sewer, which, in this study, serves as a proxy for sewer failure. Moreover, the standardized Dutch sewer condition assessment provides a universal methodology that does not require the development of location-specific models, making it relatively straightforward to implement.

The sewer condition assessment categorizes the assessment results into three intervention measures: "intervene," "warning," and "no action," which correspond to different levels of failure likelihood . These categories enable a rough estimation of the failure probability in the risk matrix, similar to the approach adapted by Koo & Ariatnam (2006). The "intervene" category indicates a failure probability of once every 10 years, prompting the need for conduit repair or replacement within a decade. The "warning" category signifies a smaller failure probability of more than once every 50 years and necessitates further research, such as additional inspections within a specified timeframe. On the other hand, the "no action" category denotes the preliminary stages of deterioration, indicating a lower failure probability that does not warrant immediate concern. Consequently, "no action" represents the lowest failure probability category in the risk matrix (Stichting RIONED, n.d.-b).

To enhance the precision of estimating the probability of sewer failure, the utilization of a comprehensive sewer deterioration model would be imperative. However, developing such a model falls beyond the scope of this research. However, to enhance the methodology of this thesis, future research efforts should aim to create a sewer deterioration model applicable to the entirety of the Netherlands.

Table 2. Combined Risk Matrix of Dordrecht (adapted from Centrum voor Regelgeving en Onderzoek in de Grond-, Water- en Wegenbouw en de Verkeerstechniek, 2014)

Organisational value				Chance	! 1x/50 years	>1x/50 years	>1x/10 years	>1x/5 years	>1x/year	1x/month
Safety	Accessibility	Reputation	Finance (damage claims)	Severity						
Accidents with fatal outcomes or very serious permanent injuries	Road section closed for a long time without diversion. Not accessible to pedestrians/cyclists	National commotion (media attention, TV, newspaper, etc)	>€100.000	5	Low	Moderate	High	Unacceptable	Unacceptable	Unacceptable
Accidents with serious injuries and long-term absenteeism	Road section closed for a short time without detour or road section closed for a long with detour or speed reduced to 15 km/h. Not accessible to disabled pedestrians/cyclists	Regional commotion (media attention, newspaper)	€50.000-€100.000	4	Low	Moderate	High	High	High	Unacceptable
Accidents with injury with absenteeism (max. 1 month)	Road section closed for a short time with diversion or road section partially closed for a long time or speed reduced to 30 km/h. Cyclists/disabled pedestrians experience serious nuisance.	Location commotion (reporting politics)	€20.000-€50.000	3	Low	Low	Moderate	High	High	High
Accidents with minor injuries (first aid without absenteeism)	Road section partially closed for a short period or limited influence on speed for a long period for pedestrians/cyclists	Few complaints, minimal effect on the image	€2500-€20.000	2	Negligible	Negligible	Low	Moderate	Moderate	High
No/negligible impact	No/negligible impact	No/negligible impact	€0-€2500	1	Negligible	Negligible	Negligible	Negligible	Low	Moderate

4.2.1 Sewer Condition Assessment

The associated measure of a sewer conduit is based on the present defect and its severity class. During a (visual) sewer inspection, defects are described to conform to the NEN-EN 13508-2:2003+A1:2011. Each defect is provided with a NEN-Code, i.e., labelled, characterized and sometimes quantified (Stichting RIONED, 2020c). A severity class is registered by the inspector; however, this is often analysed again by the sewer manager to give a final judgment. To illustrate, some examples of NEN-coding of sewer defects:

- NEN-code: BAA|A|#|#|4
    - Defect: Deformation (code: BAA)
    - Characterisation 1: vertical (A)
    - Characterisation 2 n/a (#)
    - Characterisation 3: n/a (#)
    - Quantification: 12%
    - Severity class: 4
- NEN-code BAB|C|B|#|5
    - Defect: Crack (Code: BAB)
    - Characterisation 1: crack type C (C)
    - Characterisation 2: in circumference (B)
    - Characterisation 3: n/a (#)
    - Severity class: 5
- NEN-Code BFF|A|#|H|2
    - Defect: infiltration (code: BBF)
    - Characterisation 1: sweating (A)
    - Characterisation 2: n/a
    - Characterisation 3: via manhole (H)
    - Severity class: 2

It is important to note that an inspector only observes the sewer conduit at a specific time and location and registers the situation. The sewer manager is responsible for the analyses, assessment and determining the follow-up action (Stichting Rioned, 2020c).

The defect and its characterisation (including quantification if required) are used to assign a severity class. The severity of a defect is expressed from 1-5, where 5 most severe. It is important to note that the severity class is specific to a defect and cannot be compared between defects, i.e., a crack of severity 5 is not as severe as an ingrown root of severity 5. The severity class of a defect is captured in a table of Stichting RIONED called: “Classificatiemethodiek van visuele inspecties,” i.e., classification methodology of visual inspections, specifically designed for the Netherlands. The classification is based on the European norm NEN-EN 13508-2:2003+A1:2011 and the older NEN 3399:2004 (Stichting RIONED, 2019).

The severity class can in turn be used to determine fitting follow-up actions. The link between a defect, its severity class and associated intervention measures are substantiated and described in the GRP (municipal sewerage plan, see section x) (Stichting RIONED, 2020a). The decision to intervene is in turn, dependent on the performance level a municipality wants to maintain for its sewer system (Stichting RIONED, n.d.-b).

At Sweco, a document called dTabSb.BOR is used that substantiates the link between a defect, its severity class, and associated measures. The dTabSb.BOR captures the average view of a municipality on when to intervene, keep an eye on, or do nothing. Sweco is often hired to fulfil the task of analysing, assessing, and determining the follow-up action by a municipality and has therefore drafted an assessment document for general use. The assessment document can be tweaked to fit the goals of the municipality if they deviate from the common perspective. Besides linking a defect and its severity to an intervention measure, its type of failure mechanism is also described according to the view of Sweco professionals. As an example, the defects mentioned above are assessed in the following:

- Deformation with NEN code: BAA|A|#|#|4, severity class: 4, failure mechanism: lack stability, intervention measure: Warning
- Crack with NEN code: BAB|C|B|#|5, severity class: 5, failure mechanism: lack of stability, intervention measure: Intervention
- Infiltration with NEN Code: BFF|A|#|H|2, severity class: 2, failure mechanism: lack of water tightness, intervention measure: No action

This study used the general perspective of municipalities captured in the dTabSb.BOR to determine the status of a defect. Specifically, the intervention categorization of defects and their corresponding failure mechanisms was utilized to selectively identify and analyse stability-related defects.

An important distinction is made in this thesis between "point" and "line" defects in sewer segments. Point defects are localized at specific points within the segment, such as an axial crack. Line defects extend along a certain length of the segment, such as surface damage or a longitudinal tear. This distinction is important for the manner in which the consequences of failure are assessed. In the appendix in section 9.2.1.1, a more in depth description can be found on how point and line defects were gathered from the inspection data.

To illustrate the application of the methodology, a specific example of defect processing using the 'Classificatiemethodiek' and 'dTabSb.BOR' is provided in the appendix in section 8.4. This example serves as a practical demonstration of the methodology's implementation and showcases how the categorization framework and relevant guidelines were utilized in the assessment and classification of defects.

Figure 12 provides an overview of the condition assessment of an inspected sewer system in Nissewaard and the entire municipality. Thereby highlighting which areas have been inspected. The letters I, W and N are used to show the associated measure of a defect: Intervene, Warning, and No action required respectively. These three categories are used as a proxy for the failure probability.

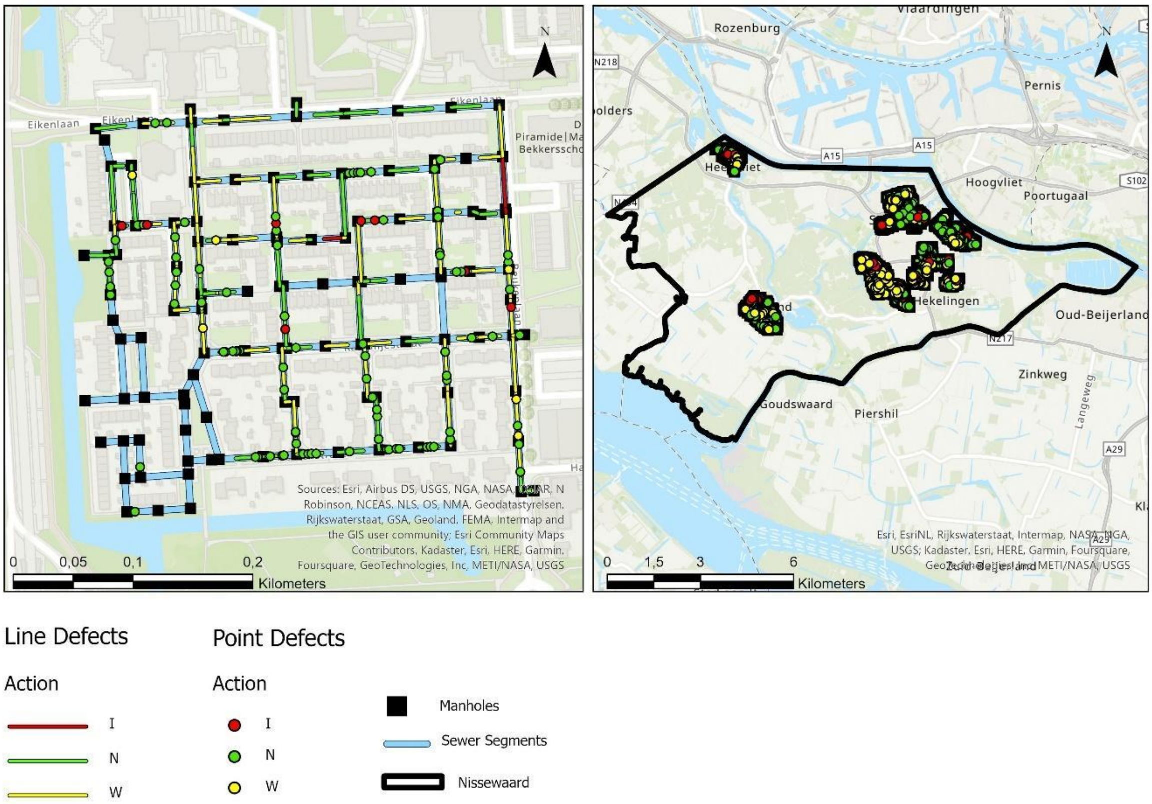

Figure 12. Condition assessment of inspected sewer in Nissewaard. On the left a zoomed-in shot of a neighbourhood in Nissewaard. On the right, the entire municipality.

4.3 CONSEQUENCES OF FAILURE

The scope of this study is limited to consequences that can 1) be spatially assessed and 2) be linked to values in the combined risk matrix. For Nissewaard, the organizational values that are impacted by sewer collapse which can be assessed are reputation, safety, accessibility, and finance. To assess the effect of sewer collapse, a buffer analysis has been carried out.

Prior studies employing buffer analysis techniques for a risk assessment have exhibited variations in their selection of buffer sizes to assign scores (Lee et al., 2021; Vladeanu & Matthews, 2019; Baah et al., 2015; Ghavami et al., 2020). The proximity of specific critical objects or spatial elements has been utilized as an indicator of the criticality of a sewer conduit, also see Figure 13. Furthermore, multiple studies have adopted a more simplified approach, focusing on the presence of conduits beneath specific roads or railroad tracks or their location within particular types of areas, such as central business districts or recreational parks (Salman & Salem, 2012; Vladeanu & Matthews, 2019; Lee et al., 2021). These studies thus only focus on the direct area above a conduit, and not necessarily on the entire area that would be impacted by sewer collapse.

Category	Factor	Score				
		5	4	3	2	1
Economic	Diameter	>900 mm	>650 mm	>450 mm	>350 mm	≤350 mm
	Length	>50 m	>30 m	>15 m	>5 m	≤5 m
	Depth	<1 m	<3 m	<7 m	<10 m	≥10 m
Social	Medical	<20 m	<50 m	<100 m	<150 m	≥150 m
	Educational	<50 m	<100 m	<150 m	<200 m	≥200 m
	Road	>7 lanes	>5 lanes	>3 lanes	>1 lane	≤1 lane
	Railway	<70 m	<120 m	<200 m	<400 m	≥400 m
	Commercial	<20 m	<50 m	<100 m	<200 m	≥200 m
	Residential	<20 m	<50 m	<100 m	<200 m	≥200 m
Environmental	River	<50 m	<150 m	<250 m	<450 m	≥450 m
	Forest	<50 m	<150 m	<250 m	<450 m	≥450 m
	Farmland	<50 m	<150 m	<250 m	<450 m	≥450 m

Figure 13. Criticality assessment used by the study by Lee et al., (2021) to determine the COF of a sewer pipe.

Therefore, unlike previous research on risk-based asset management, an approach inspired by Mekel (2020) was used to determine the consequences of failure. Mekel's thesis primarily focuses on establishing the consequences of failure for both sewer and drinking water networks. By utilizing the sinkhole radius as the buffer radius, a more precise evaluation of sewer collapse can be conducted, thereby surpassing the use of seemingly arbitrary radius dimensions, as depicted in Figure 13. Consequently, this study adopts the sinkhole as buffer to analyse the consequences of sewer collapse, thereby combining research efforts on risk assessment and consequence assessment in the field of sewer failure research. Overall, this should lead to a more accurate and comprehensive risk assessment.

To determine the size of a sinkhole the following formula was used:

$$D_s = W + 2 \cdot \frac{Z}{tan\ tan\ \theta}$$

With

D_s : Diameter of the sinkhole [m]

W : External width of the conduit [m]

Z : Ground cover on top of the conduit [m]

θ : Angle of repose [°]

The formula requires the use of the external width of the conduit, however, only the internal diameter of conduits was known.

Therefore, the internal diameter was used instead. The size of the sinkhole will therefore be slightly underestimated, but the difference is expected to be negligible. Firstly, the wall thickness is often in the order of magnitude 5-12cm for concrete and PVC 1-2cm (National Industries Company, n.d.). The most common internal pipe diameter is 400 mm in Nissewaard. According to National Industries Company, a concrete pipe with a 400 mm internal diameter has a wall width of 70 mm, and thus an external diameter of 540 mm. When studying the formula and figure, it becomes clear that the right side of the formula contributes a much larger value to the diameter of the sinkhole. As an example, a pipe with a 400 mm diameter, a depth of 2 meters and an angle of repose of 34 degrees gives

$$D_s = 0.4 + 2 * \frac{2}{tan\,(34)}$$

$$D_s = 0.4 + 5.93 = 6.3$$

Whilst if the actual external width would be filled in the formula, namely 0.54, $D_s$is 6.47, which is an increase of 2.2%, and could therefore be considered negligible on this scale.

For point defects the exact depth of the location of the defect was used, for line defects, the average depth of the line defect was taken. The angle of repose was determined to be 34°, as according to a study by Al-Hashemi & Al-Amoudi, the angle of repose of sand is 34°. When a sewer is installed, a trench is dug. After the sewer conduit has been placed, the trench is filled with sandy soil and then tamped and compacted with vibrating rammers (OCW & Vlario, 2020; Volandis, 2003).

To evaluate the consequences associated with each defect, a meticulous analysis was undertaken to determine the diameter of the sinkhole that would ensue in the event of collapse. Subsequently, a buffer was generated for every defect, including both line and point defects. In this context, the radius of the sinkhole was employed as the buffer distance, effectively depicting the spatial extent of a sinkhole on the map. Specifically, for point defects, a circular buffer was generated surrounding the precise location of the defect. In the case of line defects, a buffer was generated in the form of a line segment with rounded edges, spanning the entire length of the observed damage. This approach was adopted due to the inherent uncertainty surrounding the exact location of conduit failure when the damage extends across a conduit. Given the uncertainty regarding the specific point of collapse, the buffer was designed to include the entire extent of the affected conduit, ensuring a complete assessment of the potential consequences associated with the line defect. A visual example illustrating this methodology can be found in Figure 14, providing a clear representation of both types of buffers.

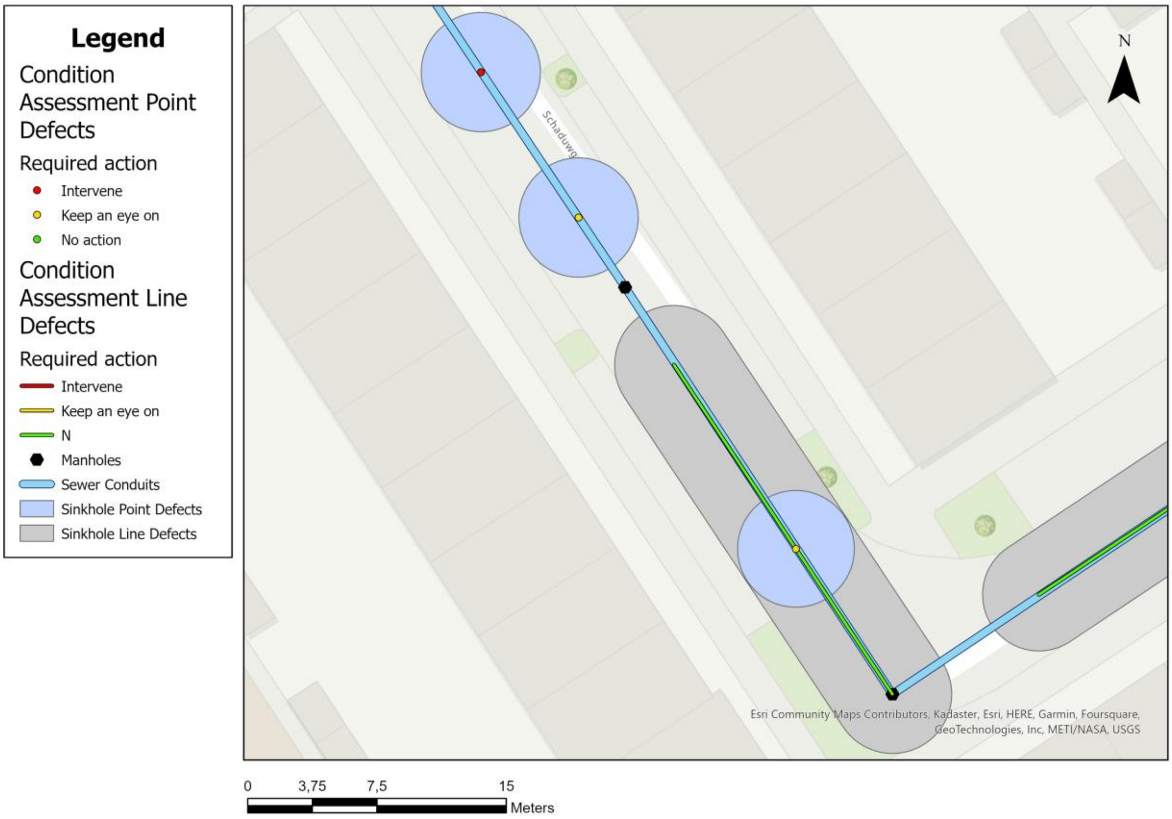

Figure 14. Sinkholes of Point and Line defects.

In order to examine the influence of a sinkhole on organizational values, a relevant factor to quantify the impact was selected to. The selected organizational values for the case study include safety, accessibility, finance, and reputation, as indicated in the integrated risk matrix. However, it is important to acknowledge the inherent challenge of determining the precise impact of a sinkhole on each organizational value, given the complex and interconnected nature of these values. Notably, organizational values exhibit strong interdependencies, whereby changes in one value may significantly affect others. For instance, a decrease in safety or accessibility, as well as substantial financial losses, can potentially lead to public uproar and detrimentally impact the municipality's reputation. Furthermore, the accessibility of an area is intimately intertwined with its safety, as compromised accessibility, such as the inability of an ambulance to reach a patient promptly, can jeopardize overall safety outcomes.

To assess the COF on organizational values, a selection process was undertaken to identify the most relevant factor for each organizational value. By envisioning plausible worst-case scenarios caused by sinkholes, the most relevant and impactful factors were selected. The factors considered to study the impact on the organizational values are damage to 1) underground infrastructure, 2) roads, and 3) buildings in general as well as 4) nearness of vulnerable buildings. For the first three factors, a shapefile was used, and its shapes were layered over the sinkhole of a defect. The fourth factor studied the vulnerability of an area by analysing the presence of a vulnerable building within a 10-meter radius of a defect.

Table 3 provides an overview of which factor was analysed to study the impact on an organizational value. Again, it is important to note that a factor often impacts multiple organizational values due to the strong connection between organizational values. Even though multiple factors influence multiple organizational values, the analysis of one factor per value suffices due to the nature of the methodology. The risk of sewer collapse is namely determined by combining the probability of failure and the most severe consequence. If one would choose to analyse multiple factors per value, one factor would always overshadow or score similarly to the other, thereby deeming the examination of another factor negligible. In this study, the organizational value that is impacted the most does also not matter for the overall risk. The risk of sewer collapse is simply the combination of the probability of sewer collapse and its worst consequences, with no distinction being made between the consequences.

Table 3. Organizational value and its associated factor to assess the impact of sewer collapse.

Organizational value	**Shapefile**	**Shapefile specification**	**Explanation**
Safety	Underground Infrastructure	Line elements with all cables and pipes	In case of a breakage of a cable or pipe, safety issues might arise depending on the type of cable or pipe. For example, in case an LPG pipe would be damaged, an explosion could follow, potentially causing multiple fatalities.
Accessibility	Roads	Polygons with all road surfaces, including their function and type	If a road is damaged, a road temporarily becomes unusable. Depending on the function and type of the road, a different number of people its accessibility to a certain area is affected.
Reputation	Vulnerable Buildings	Polygons of buildings with a special societal function or high vulnerability (e.g., storage of dangerous substances)	A sinkhole near a vulnerable location results in a decrease in accessibility and/or safety. This could lead to complaints and even large-scale commotion. For example, in case a hospital its accessibility is hindered, commotion is to be expected.
Finance	(Basic Registration Addresses and Buildings)	Polygons of all buildings and homes	A building damaged by a sinkhole could cause great financial damage,

			depending on its function (e.g., home, public). It could result both in direct damage, e.g., foundation damage and indirect damage, e.g., a building rendered temporary/permanently unusable which could cause the inability to perform work and lost income as a result.

4.3.1 Determination of Consequence of Structural Sewer Failure

This section denotes how each factor was used to study the impact of a sinkhole on an organizational value. Moreover, the consequence of failure (COF) caused by a sinkhole on the organizational value is described. The COF is ascribed a numerical score ranging from one to five, with five denoting the utmost severity.

4.3.1.1 Sinkhole nearby Vulnerable Buildings

Damage to the reputation of Nissewaard is quantified by studying the presence of critical buildings in a radius of 10 meters. 10 meters was deemed a suitable range to see the affected buildings as a similar range was used by previous research by Lee et al., (2021) and Vladeanu & Matthews (2019).

A critical location is defined as a building that either serves an important societal function or is home to vulnerable groups. The buildings considered are based on shapefiles provided by Nissewaard, one contained polygons of special objects/buildings, the other of vulnerable buildings. It is assumed that these buildings represent the values of Nissewaard regarding what a critical location is. Table 4 provides an overview of the COF of a sinkhole near a critical building on the organizational value reputation.

Table 4. Overview of how the presence of vulnerable buildings relates to the level of effect.

Building	COF	Reasoning
● Municipal building ● Museums and monuments ● Parking garage ● Pumping station ● Animal shelter ● ITC centre ● Navigation and shipping posts	1	These buildings have a function for the community but the need for accessibility for emergency transport is low compared to the other buildings seen as vulnerable If these buildings are temporarily slightly less accessible, no commotion is expected.

• Elderly homes • Physically and/or mentally disabled homes • Waste processing • Sewage treatment plant	2	There is a need to be accessible for (emergency) transport otherwise complaints will for sure follow.
• Nursing and care homes • Production centres • Prison	3	For nursing homes, the need to be accessible for healthcare employees and emergency transport is high. For production centres, accessibility for trucks is crucial to ensure no financial damage occurs. If the accessibility of these buildings is hindered, local commotion is to be expected.
• Schools • Gas station	4	Education buildings need to be accessible as it serves many people, additionally, a sinkhole near a location with underage persons, i.e., children, teens, etc. is a safety hazard. A sinkhole near a gas station could also cause safety issues due to the underground storage of fuel. The threat to safety could cause commotion. Additionally, a gas station is visited by many people each day. Therefore, if a sinkhole occurs is the vicinity of these buildings, regional commotion could be expected.
• Fire station • Police station • Hospitals and health clinics • Storage locations of dangerous substances	5	The police and fire station as well as a hospital or health clinic rely on being accessible as they often deal with emergencies. If damage is done near the storage of dangerous substances, a hazardous situation could be the result. Both cases could lead to national commotion.

4.3.1.2 Damage to underground infrastructure

To assess the impact of a sinkhole on safety, the damage to underground infrastructure was assessed. Damage to underground infrastructure can create a hazardous situation. A shapefile containing all underground infrastructure in Nissewaard, both pipes and cables, was used for the assessment. Table 5 describes the COF of sewer collapse on the organizational value: safety.

Table 5. An overview of the associated effect level in case a pipe or cable is within a sinkhole.

Type of cable/pipe	COF	Reasoning
• Out-of-order electricity cable • Out-of-order gas pipe • Municipal stray pipe • Out-of-order telecom • Out-of-order common drinking water	n/a	Cables or pipes that are out of use will not cause inconvenience if damaged.
• Municipal camera cable • Municipal parking management sign data cables (barriers) • Municipal telecom • Municipal traffic control installation • Other cable or pipe • Common telecom	1	Cables that are used for traffic control, cameras, parking systems or telecom do not endanger the safety of passengers, additionally, the inconvenience caused to users of the cables is negligible. Additionally, due to their limited depth, they are more easily repaired.
• Common electricity cable	2	Due to the high dependency of society on electricity, the inconvenience caused by a lack of electricity is higher than that of a telecom cable. Damage to the power cable can potentially cause a short circuit. The chance of this is not very great due to the protection measures and the early detection of leaks that cause an immediate power failure. Therefore, the safety risk is low.
• Common drinking water	3	A burst water pipe releases a lot of water and households are often temporarily without water. The street or road is also often flooded, which can lead to a dangerous traffic situation, potentially causing injuries. In the event of a leak in the water pipe, the drinking water can become contaminated endangering the health of those that consume it.
• Public transport electricity cable • Low-pressure gas pipe • Transport pipe (pressurised) • Heat network	4	If a public transport electricity cable or pressurised pipe is damaged, many people are affected. Moreover, the repair is more difficult and requires more time. Damage to low-pressure gas or a heat network pipe can cause a seriously

		dangerous situation. A broken gas pipe can cause an explosion whilst a heat network pipe can cause a fountain of hot water which is dangerous for bystanders, causing serious injuries.
● LPG ● High-pressure gas pipe	5	Damage to an LPG or high-pressure gas pipe is even more dangerous than a low-pressure gas pipe as the probability of an explosion rises, with possibly lethal consequences.

If a pipe or cable overlapped with the sinkhole, the respective effect score as stated in Table 5 was attributed to a defect. If multiple pipes and/or cables were affected by a sinkhole, the score of the most critical element was taken as representative of the COF. For example, if a water supply line and a lower-pressure gas pipe would be damaged, the gas pipe has a higher COF, and thus the defect would be assigned a COF score of 4. Figure 15 shows the shapefile that is used to assess the safety implications of a sinkhole.

Figure 15. An indication of the spatial layer containing all pipes and cables of Nissewaard (Municipality Nissewaard, 2023).

4.3.1.3 Damage to Roads

To determine the severity level of the consequence of a sinkhole regarding the accessibility of an area in Nissewaard, a shapefile containing polygons of every road, categorized on its function, was used. The accessibility of an area is namely strongly dependent on the roads or paths leading in and out of an area.

Within the shapefile, a road is given both a type and a function. Both element were used to assess the impact of a sinkhole on the accessibility on an area. Tables 6 & 7 show the overview of all categories present in both columns.

Road type
None
Roads with heavy traffic
Road with moderate traffic
Road with light traffic
Residence road
Residential road (footpath)
Cycle path
Unknown

Table 6. Road types as defined by Nissewaard.

Road function
None
Bus lane
Cycle path
Entrance road
Parking lane
Parking place
Roadway
Bridle path
Speedbump
Pedestrian area
Footpath
Footpath on stairs

Table 7. Road functions as defined by Nissewaard.

The road functions and road type were both used to create 5 groups with different ascending levels of consequences for accessibility in case a road is damaged. Both the function and type of the road were used, since the road function does not make a distinction between pedestrian paths, parking spaces, or cycle paths that are shared with another type of road, e.g., a residence road. According to the risk matrix, a parking space or footpath has limited consequences on the accessibility of an area, therefore it was important to make this distinction. Table 8 provides an overview of how the road type and road function determine the COF of sewer collapse on accessibility. Figures 17 and 18 provide an overview of the spatial layer used to determine the effect of accessibility in the case of sinkhole formation.

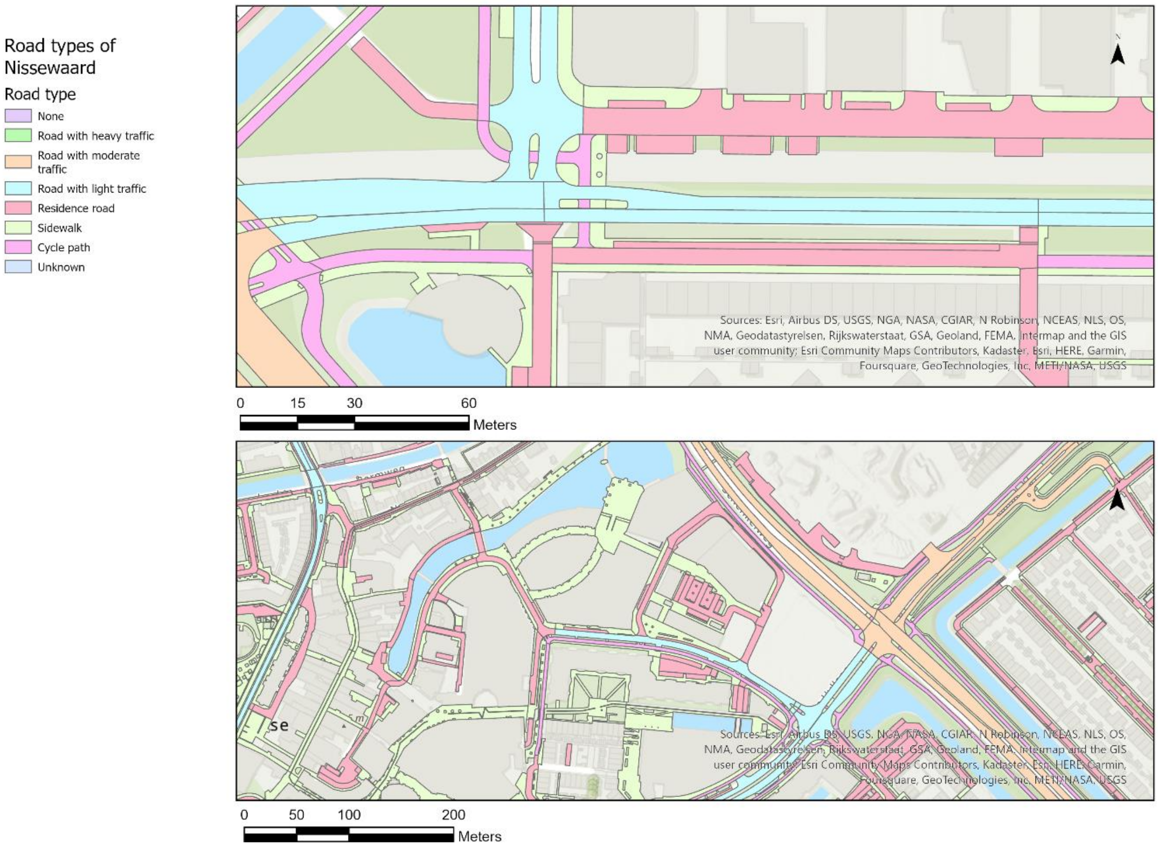

Figure 17. Indication of Road types in Nissewaard.

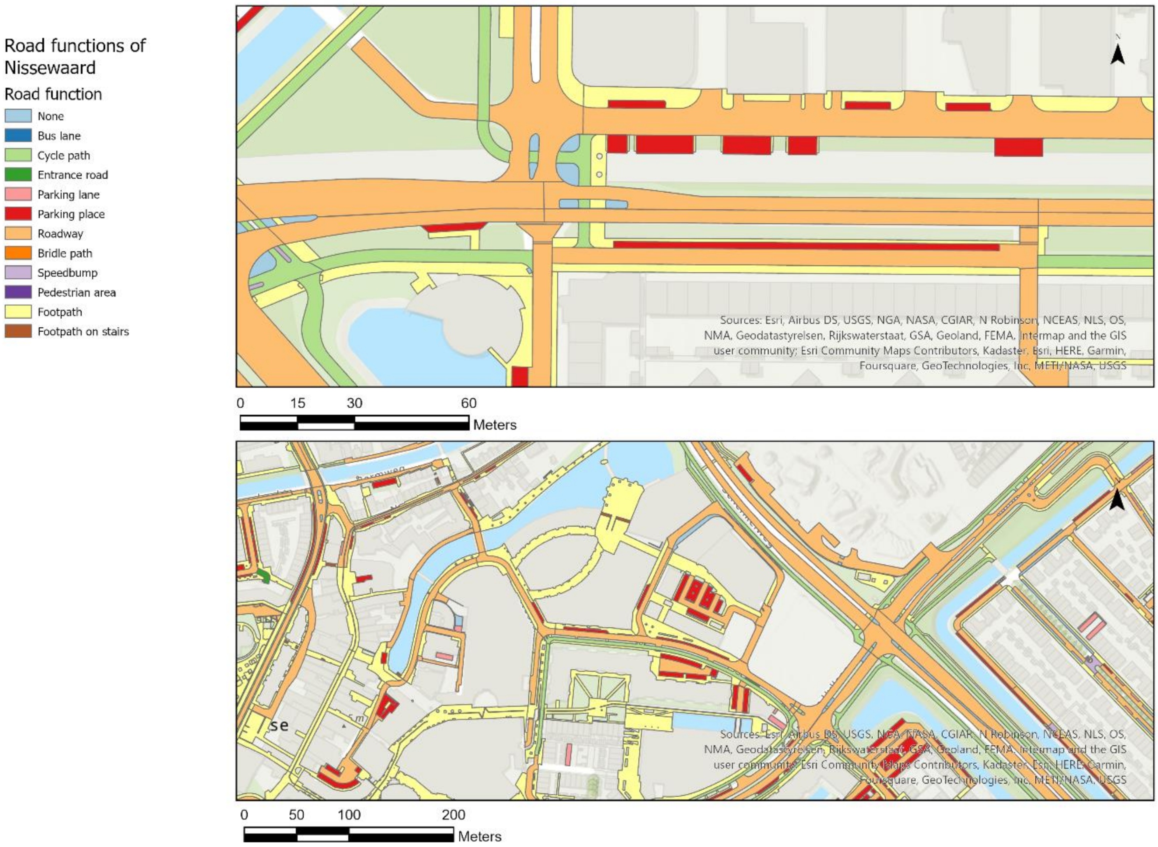

Figure 18. Indication of road function in Nissewaard.

Table 8. Overview of how the road type and road function determine the level of effect.

Road type	Road function	COF	Reasoning
• Parking lane • Parking place • Footpath • Footpath on stairs • Pedestrian area • Cycle path	Can contain all road functions, but most often: • Residential road • Cycle path	1	The accessibility of an area in case of damage to a parking place, footpath or cycle path is limited as there is often an alternative route available.
n/a	Residence road	2	In case a residence road is damaged, an area can become inaccessible for a while. For cars, there might not always be an alternative route available. However, as residence roads often serve a smaller public, the affected group is small.
n/a	Light traffic	3	A road with light traffic serves a larger group of people and can be an important route for emergency services.
n/a	Moderate traffic	4	A road with moderate traffic can cause serious hinder to a large group of people and emergency services, causing traffic delays. Additionally, other routes might be subjected to a heavier traffic load, which can cause nuisances.
n/a	Heavy traffic	5	Roads with a heavy traffic load affect the highest number of people, are often the main routes for help services and can cause huge traffic delays.

Then in an similar manner to how the severity of consequences was determined for the damage to underground infrastructure, each sinkhole was intersected with the polygons of roads to assess which road(s) were affected by a sinkhole formation. Again, the most critical road damaged and its respective COF was attributed to a defect.

4.3.1.4 Damage to Buildings

The financial damage to buildings due to a sinkhole is used to assess the financial consequences of a sinkhole. It is assumed that damage to a building would lead to the highest costs of all spatial objects that could be damaged. Therefore, it can be used to study the impact of a sinkhole on the organisational value: finance.

The Basisregistratie Adressen en Gebouwen (BAG), i.e., Key Register Addresses and Buildings, is an open dataset of PDOK. It was used to assess which and how many buildings would be damaged by a sinkhole. The BAG contains polygons of every building in the Netherlands, and these were layered over the sinkholes. Unfortunately, the BAG has no information on the "waarde van onroerende zaken" (WOZ), i.e., the valuation of real estate. Therefore, the amount of financial damage will be based on the function of the building, inspired by the approach of STOWA to assess the potential water damage in case of high-water levels. The BAG considers the functions as seen in Table 9. These functions will be used to distinguish the amount of financial damage a sinkhole brings about.

Table 9. Functions of buildings registered in the BAG.

Function	Description
Residential	Used for living, a home
Meeting	For the gathering of people for art, religion, culture, childcare, communication, or general meetings
Cell	Compulsory stay of persons, prison
Healthcare	Medical research, nursing, treatment, or care
Industrial	Commercial storage or production of goods and materials, or for agricultural purposes
Temporary Accommodation	Recreational or temporary accommodation for people
Education	Used for Teaching
Sports	For the practising of sports
Shop	Trading of goods, services or materials
Other	None of the above, e.g., sheds

The amount of financial damage is assessed by using a report which is the basis of a STOWA application that determines the financial damage in case of water damage (waterschadeschatter) (STOWA, n.d.). This report links the BAG functions to the average amount of direct and indirect damage. Whilst the costs of water damage are different from the costs of collapse due to a sinkhole, the amount of costs associated with each building function still represents the relative importance of a building. In other words, a building with high indirect costs from water damage, will likely also have higher indirect costs due to prolapse than a building with relatively low indirect damage from water damage.

Often a sinkhole barely touches an outer wall of a building, however, this could still cause considerable damage to the foundation and or walls and could potentially lead to collapse. Additionally, private house connections might be damaged, which could also have serious implications as it could cause water damage and/or the need for immediate repair. Table 10 shows the COF of sewer collapse on the organizational value: Finance.

Table 10. Overview of building functions and their related level of effect based on expected financial damage.

Building Function	**COF**	**Reasoning**
• Other	2	Other often includes sheds, which in case of a sinkhole will have relatively little direct or indirect costs. The expected costs are about €2.500-€25.000 to restore the damage.
• Cell • Sport	3	Relatively lower direct costs to the building. Damage is expected to be on average between €20.00-€50.000
• Family home • Gathering	4	High direct costs, but relatively low indirect costs, i.e., no to little societal disruption. On average damage will remain below €100.000
• Healthcare • Education • Industrial • Shop • Office • Temporary Accommodation • Apartment building	5	High direct and indirect costs. Indirect costs are high due to societal disruption, where multiple people are affected. In case of damage, it is expected to be above €100.000

4.4 RISK ASSESSMENT

After the spatial analysis, each defect has been attributed a COF for the impact on all organizational values. In case no intersect was found with a buffer and the factor used to study the impact on the organizational value, a COF of 1 (negligible impact) was attributed. This means that after the spatial analysis, a defect has been given a separate COF score of 1 to 5 for each organizational value representative of the impact of a sinkhole on that value. Then, considering all organizational values, the highest COF score, i.e., the worst possible consequence of a sinkhole, is taken to determine the severity of the defect. This approach is inspired by the method adopted by Koo & Ariaratnam (2006) and reflects the philosophy "A chain is only as strong as the weakest link" or in this case, a sewer collapse is as disruptive as its greatest consequence.

The highest severity score of a defect and the probability of sewer failure were taken to assess the level of risk using the risk matrix of Dordrecht. As the probability of failure (POF) was divided into three groups of probability, only three out of six columns of the combined risk matrix were used regarding the chance of sewer collapse. Table 11 shows the section of the risk matrix that was used for the risk analysis. It is important to note that the COF is based on the organizational values: safety, reputation, finance, and accessibility as discussed above, but the description of the impact has been left out to improve the readability of the matrix.

Table 11. The condensed risk matrix of Dordrecht, used to assign the level of risk of sewer collapse. The probability of failure is based on the sewer condition assessment. The COF is determined by taking the highest impact a sinkhole can cause on one of the organizational values: safety, finance, accessibility, and reputation

POF **COF**	**1 x /50 years** (No action required)	**> 1 x /50 years** (Warning)	**1 x/10 years** (Intervene)
5	Low	Moderate	High
4	Low	Moderate	High
3	Low	Low	Moderate
2	Negligible	Negligible	Low
1	Negligible	Negligible	Negligible

4.5 Comparison Conventional and Risk-Based Asset Management

To assess the difference between sewer asset management and risk-based sewer asset management, a sewer replacement scheme has been developed for both approaches. For conventional sewer asset management, sewer conduits are replaced or repaired if a conduit has a defect needing intervention (Stichting RIONED, n.d.-b) This study assumes that when applying a risk-based sewer asset management approach, an asset manager would replace a conduit if it contained a high-risk defect.

In the context of sewer conduit rehabilitation, an alternative option to conduit replacement is relining, which involves the application of a resin-impregnated stocking to create a new sewer conduit within the existing one (Stichting RIONED, 2021a). While relining may be a more cost-effective option compared to replacement, the focus of this study is not on determining the actual costs of each strategy but rather on comparing the cost ratios between them. Relining can also not be applied in every situation, e.g. deformed conduits cannot be rehabilitated by relining. By assuming rehabilitation entails conduit replacement for simplicity, the study aims to highlight the differences between two distinct asset management approaches. It is worth noting that the implementation of relining is likely to result in a similar cost ratio, as the costs per square meter are lower, but the total number and length of conduits requiring rehabilitation remain unchanged. The purpose of the costs calculation is to emphasize the relative cost differences between the two strategies rather than determining their actual costs.

4.5.1 Costs of Rehabilitation

To determine the costs for the municipality to replace the sewer conduits in need of repair, the cost indicators of Stichting RIONED for gravity sewer conduit repair have been used (Stichting RIONED, 2021a). Table 12 shows the expected costs of sewer conduit repair in January 2021 for a round conduit with a diameter of 300 mm and 700 mm.

Table 12. Cost indicators of sewer conduit replacement for a round 300 mm and 700 mm conduit in January 2021. The table was adapted from Stichting RIONED (2021a).

Costs Component	**Round conduit 300 mm in January 2023** **[in €/m]**	**Round Conduit 700 mm in January 2023** **[in €/m]**
1. Conduit	55	221
2. Groundwork	62	140
3. Paving	174	247
4. Miscellaneous	36	56
Cost indication excl. surcharges	330	660
5. Surcharges	136	277
Cost indication incl. surcharges	470	940

The prices of sewer replacement have been indexed to April 2023 to account for inflation. Since 2021, the prices have risen 22%. The cost indication including surcharges of a round 300 mm and 700 mm conduit are €576.2/m and €1152.5/m, respectively (Stichting RIONED, 2022; Centraal Bureau voor de Statistiek, 2023).

The costs determination of other diameters makes use of these costs using the following formulas:

1) For diameters smaller than 700 mm:

$$CI = BC_{300} * 1.25^{\frac{(D-300)}{135}}$$

For diameters equal to or larger than 700 mm:

$$CI = BC_{700} * 1.17^{\frac{(D-700)}{135}}$$

With

$$CI: Cost\ Indication\ of\ conduit\ repair\ \left[\frac{€}{m}\right]$$

$$BC_{300}: Base\ Costs\ of\ round\ 300\ mm\ conduit\ \left[\frac{€}{m}\right]$$

$$BC_{700}: Base\ Costs\ of\ round\ 700\ mm\ conduit\ \left[\frac{€}{m}\right]$$

$$D: Diameter\ [m]$$

For egg-shaped conduits, the width is considered the diameter, see Figure 19.

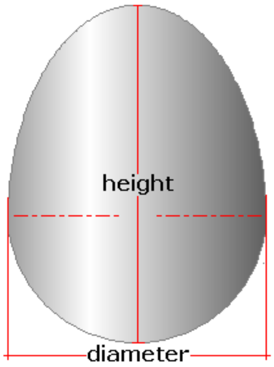

Figure 19. Egg-shaped conduit (Spike's calculators, n.d.)

To determine the costs of conduit replacement, the costs in euros per square meter were determined by filling in one of the formulas above, depending on its diameter and multiplying it by the length of said conduit. In other words:

$$Replacement\ costs\ conduit\ [€] = CI\ \left[\frac{€}{m}\right] * length\ conduit\ [m]$$

For both replacement strategies, i.e., based on the current and risk-based approach, the total costs for the municipality were determined by summing the costs of all conduits that needed to be replaced. The results can be found in the next chapter.

4.5.2 Risk After Rehabilitation

To study the remaining risk after conduit replacement for both the risk-based and current asset management approach, the risk of the entire sewer conduit was determined. This was achieved by taking the highest risk defect as representative of the risk for the entire conduit. Relying once again on the principle a chain is as strong as its weakest link. The same approach was applied to the condition assessment, where the worst condition of a defect was used as a representative for the sewer conduit condition.

For both replacement strategies, a conduit that was replaced was given a risk level of "None". Theoretically, no defects should be present in the new conduits, meaning the conduit does not have any vulnerable spots on which a spatial analysis can be performed. The result on the risk of sewer collapse after conduit rehabilitation is shown in section x.

4.6 Tools and Materials

The data and software used and their accessibility are presented in Tables 13 and 14, respectively. In the appendix, a more in-depth description is given of how the data and software have been used. To be able to repeat this study, FME is not a requirement, it only makes the process easier and automated. For data visualization, Arc GIS Pro could be substituted for the free GIS tool: QGIS. Due to the availability of ArcGIS PRO and the personal preference for the software, ArcGIS Pro has been used.

Table 13. Overview of utilized software.

Software	Description	Accessibility
Visual Studio Code	Software for programming. This study used it for writing a Python script to transform the Ribx files into a shapefile	Freely available
FME	Software to create automated workflows for data transformation and analysis.	License required
ArcGIS Pro	Desktop application for data visualization, transformation, and analysis. This study only uses it for data visualization.	License required

Table 14. Overview of utilized materials

Data	Data description	Manner of access	Accessibility
32 Ribx Files	XML files containing the results of the visual sewer inspections. Data is formatted according to the NEN-	Provided by the municipality of Nissewaard	Limited: on request
Actueel Hoogtebestand (AHN 4 DTM 0.5m)	Digital terrain model of the Netherlands with a resolution of 0.5m	PDOK	Freely available
Classificatiemethodiek	Excel file on how to classify sewer defects	Stichting RIONED	Available with a Stichting RIONED account
dTabSb.BOR	Text file linking classified defects to an intervention measure	Sweco	Limited: Only for Sweco employees
Underground Infrastructure shapefile	Shapefile with lines representing all cables and pipes of Nissewaard	Municipality of Nissewaard	Limited: on request
Vulnerable buildings shapefile	Shapefile of all objects and buildings that have a special function or are vulnerable	Municipality of Nissewaard	Limited: on request
Road's shapefile	Shapefile with all road surfaces in Nissewaard	Municipality of Nissewaard	Limited: on request
BAG	Shapefile with all buildings in the Netherlands	PDOK	Freely available

5 RESULTS

This chapter compares the condition and risk assessment of the inspected sewer systems in Nissewaard. An overview is provided of the replacement plans and their associated costs. Lastly, two areas within Nissewaard are presented in maps to highlight the difference between the condition and risk assessment and their associated replacement strategies.

5.1 CONDITION AND RISK ASSESSMENT

Tables 15 and 16 provide an overview of the distribution of the condition and risk assessment of defects respectively. As seen in Table 15, almost two-thirds of the defects have been labelled as “No action”, meaning that most defects do not require any form of attention yet according to the current asset management approach. Only 6% of the defects require intervention in the current sewer asset management approach.

If we study the results of the risk assessment, even a smaller percentage of the defects would require rehabilitation efforts, namely 3% of the total. Around half of the defects have a low risk of collapse. Figure 19 and Table 18 present the distribution of risk within the three sewer conditions. The first column, on the right, shows that ‘No Action”-defects are either given a low or negligible risk. 78% of the “No Action’-defects are assessed as having a low risk. ‘Warning’-defects are most commonly assigned a moderate risk, followed by negligible risk, with only a small portion receiving the label of low risk. For intervention defects, over half have a high risk, and the other 43% is relatively equally distributed over negligible, low and moderate risk, with the highest proportion being low. Most often, the impact on the organizational factor: Safety is the reason a defect is associated with a high risk. The allocation of a high-risk level to a defect and the proportion of its cause, i.e. which organizational value was impacted, is shown in Table 17.

Table 15. Distribution condition assessment

Condition Assessment	Proportion of Total [%]
No action	63%
Warning	31%
Intervene	6%

Table 16. Distribution risk assessment

Risk Assessment	Proportion of Total [%]
Negligible	21%
Low	52%
Moderate	23%
High	3%

Table 17. The proportion of high risk caused by the impact of sewer collapse on an organizational value.

Cause of high risk	Proportion of total [%]
Safety	91%
Finance	7%
Accessibility	1%
Reputation	1%

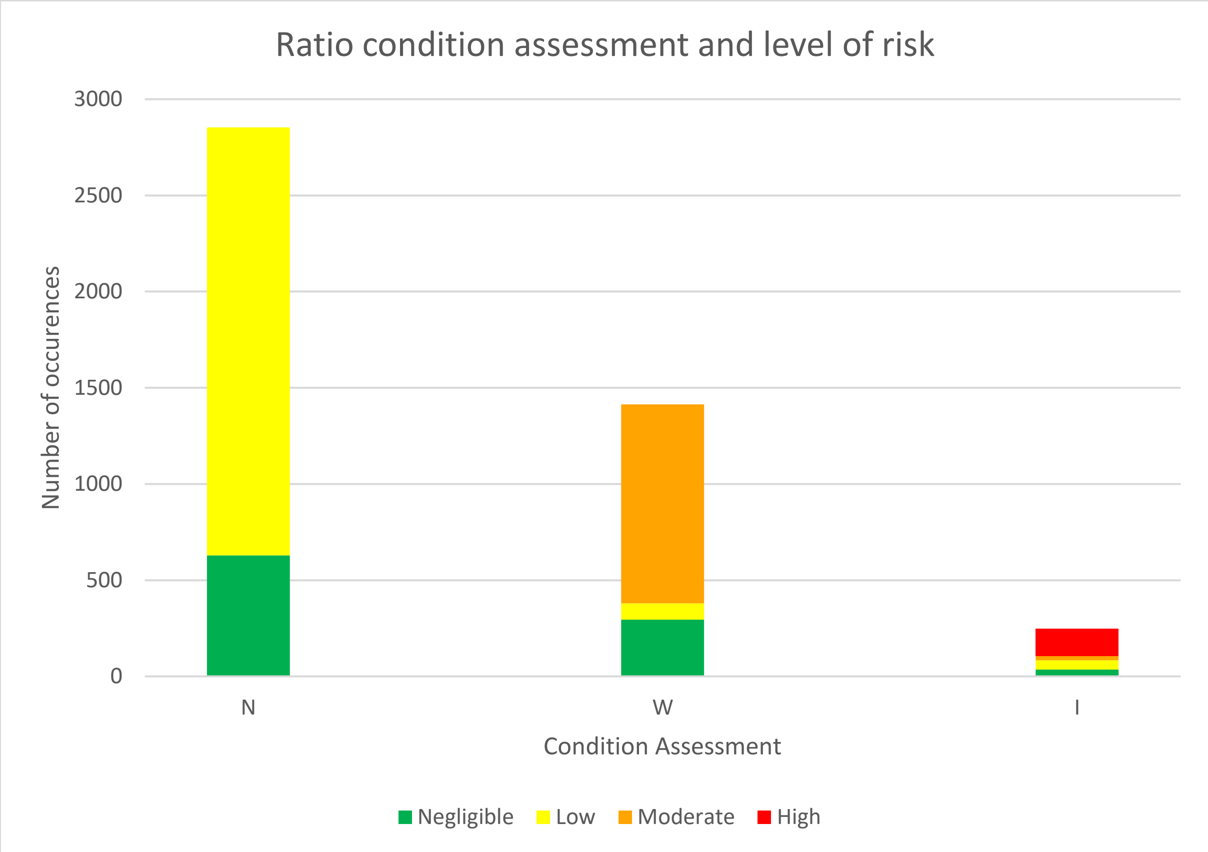

Figure 19. Distribution of risk for each sewer condition assessment.

Table 18. Distribution of risk per condition category.

	No action	Warning	Intervene
Risk	***[%]***	***[%]***	***[%]***
Negligible	22%	21%	14%
Low	78%	6%	19%
Moderate	0%	73%	10%
High	0%	0%	57%

5.2 SEWER REHABILITATION

5.2.1 Costs

To highlight the difference between sewer asset management and risk-based sewer asset management, two replacement plans have been developed. In the current sewer asset management approach, a sewer conduit is rehabilitated if it suffers from a defect needing intervention. For the risk-based sewer asset management approach, it is assumed a sewer conduit is rehabilitated if a conduit contained a high-risk defect. Using these criteria for both approaches, two replacement schemes were created, of which the specifics are shown in Table 19.

For the current replacement strategy, much more effort is required; almost twice as many conduits need to be replaced. The needed investment costs are evidently also much higher for the current approach. For the risk-based approach, an initial investment of around 2.7 million euros is needed, whilst for the current approach 4.2 million euros are required.

Table 19. Costs of sewer conduit replacement for the current and risk-based sewer asset management rehabilitation strategy.

Replacement based on risk		Replacement based on condition	
Number of conduits	123	Number of conduits	201
Length	3988.0m	Length	6516.1m
Costs	€2,674,894.10	Costs	€4,195,639.60

5.2.2 Risk after Rehabilitation

The proportion of risk that remains after conduit replacement for both the current and risk-based sewer asset management rehabilitation strategy is shown in Table 20. The differences are quite subtle, the risk-based removal has a slightly higher percentage of low and moderate-risk conduits remaining. For both strategies, 6% or less per cent had to be removed, thus also causing only a slight difference in the distribution of risk after rehabilitation.

Table 20. The proportion of risk remaining after applying the current and risk-based rehabilitation scheme.

	After High-risk conduit removal	**After "Intervention"-conduit removal**
Risk	Proportion of total [%]	Proportion of total[%]
None	39%	41%
Negligible	10%	10%
Low	33%	32%
Moderate	19%	18%

5.3 VISUAL OVERVIEW OF RESULTS

To paint the picture of the difference between the condition and risk assessment and their associated rehabilitation efforts, several maps of inspected sewer systems in Nissewaard are exhibited.

5.3.1 Example 1: Groenewoud

In Figure 20 the condition assessment of the sewer system of part of the neighbourhood of Groenewoud is shown. Both point and line defects are portrayed. Figure 21 shows the complementary rehabilitation plan, where conduits that need to be replaced due to the presence of an intervention defect are coloured pink. For this specific area, 13 conduits would need to be replaced which would cost around €346,300,-.

The risk assessment of the same area is demonstrated in Figure 22. As seen, there are slightly fewer red points and lines compared to the condition assessment. For example, on the west side of the condition assessment map, two red dots are visible, which have turned green and yellow in the risk overview. The replacement plan based on the risk assessment is showcased in Figure 23. Slightly fewer conduits need to be replaced compared to the current approach, which results in an investment decrease of seventy thousand euros.

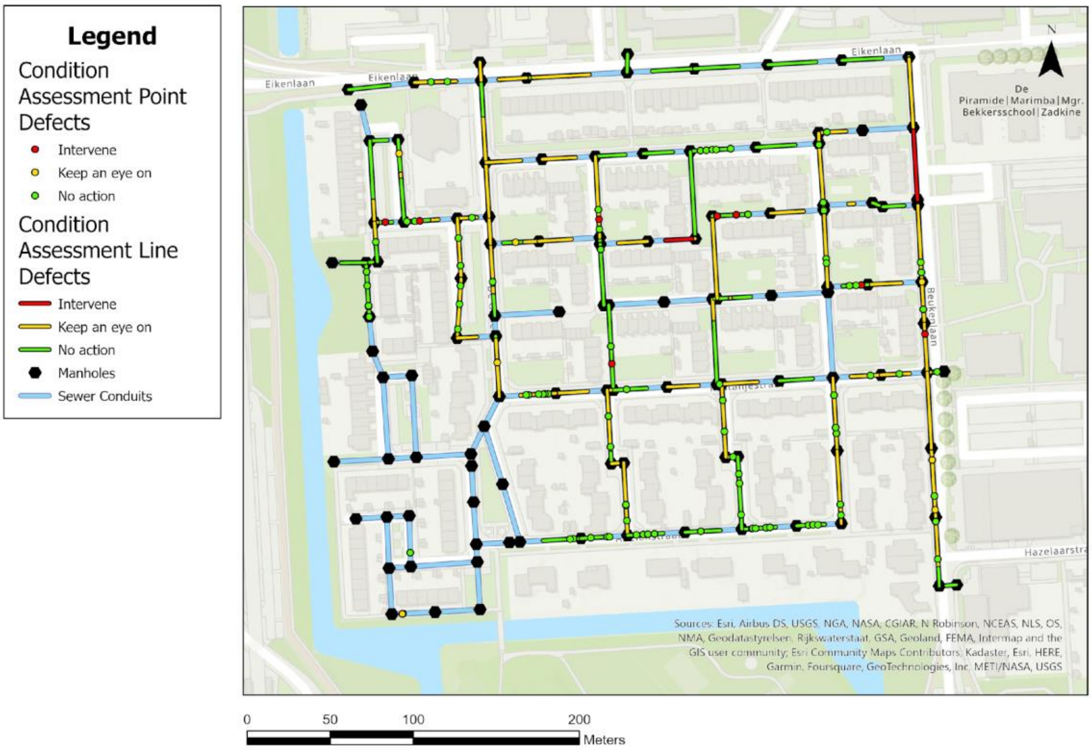

Figure 20 Condition assessment of defects in the neighbourhood of Groenewoud.

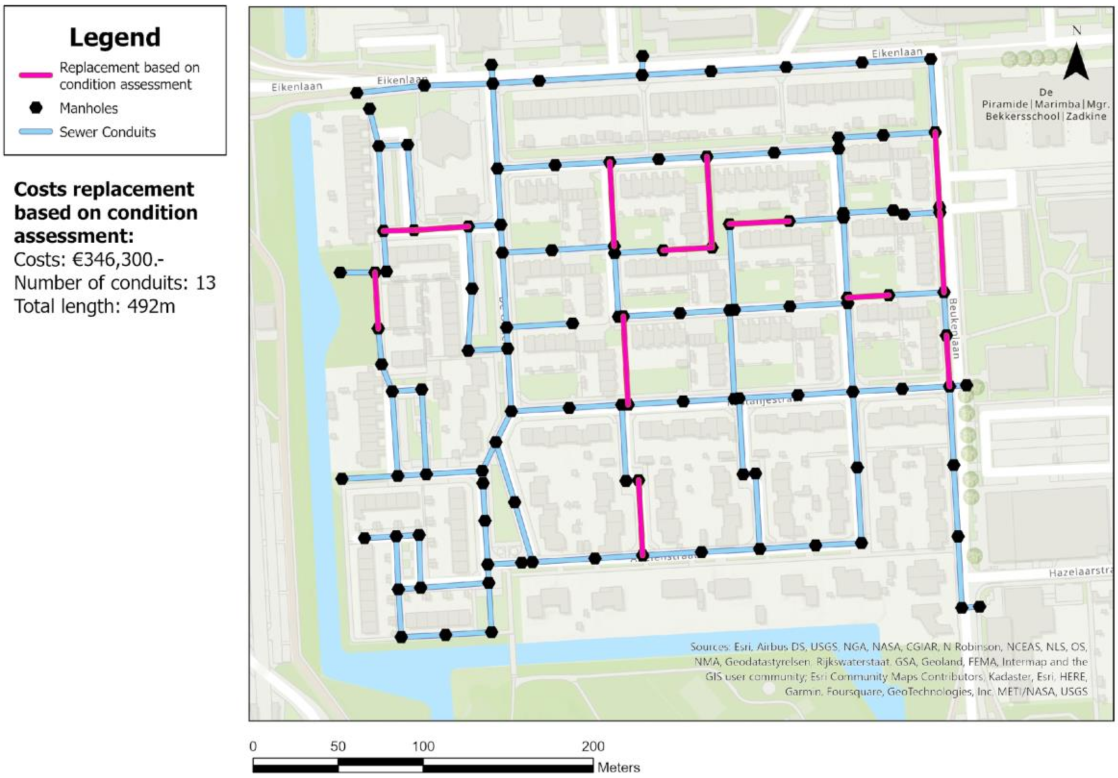

Figure 21. Sewer rehabilitation planning following the current sewer asset management strategy, with conduits scheduled for replacement shown in pink.

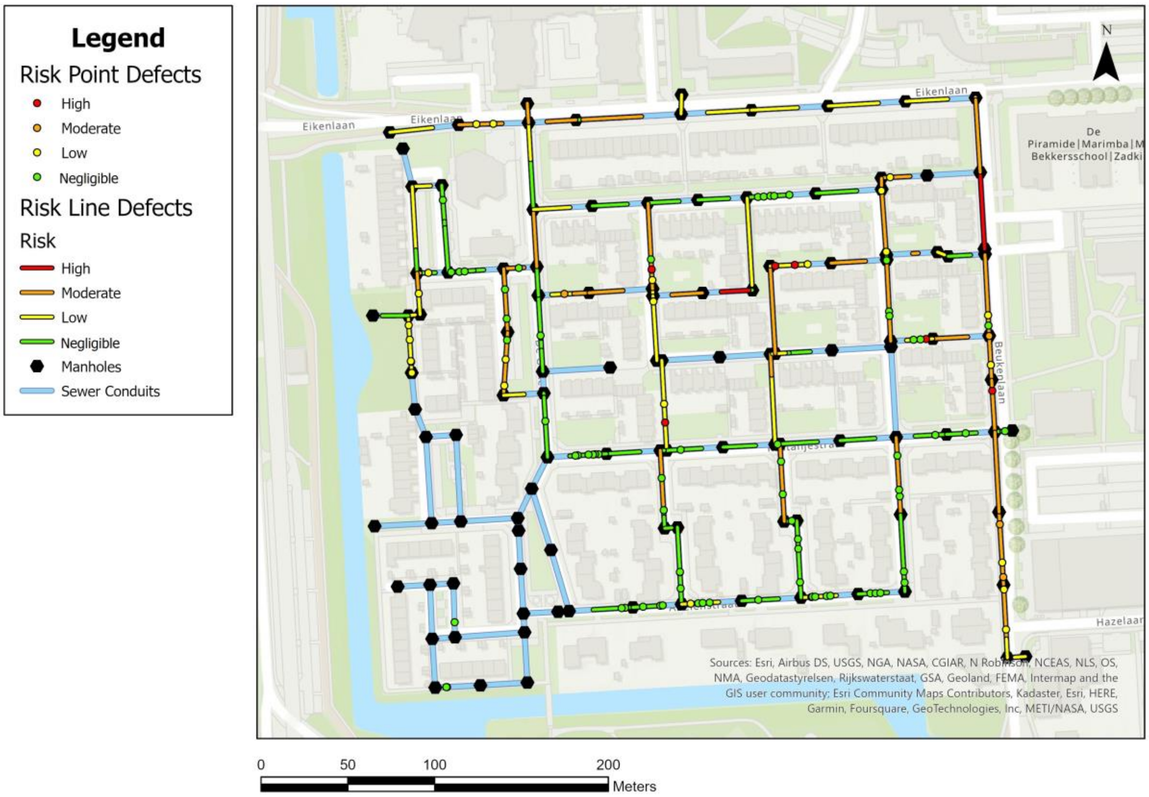

Figure 22. Risk assessment of sewer defect in the neighbourhood of Groenewoud.

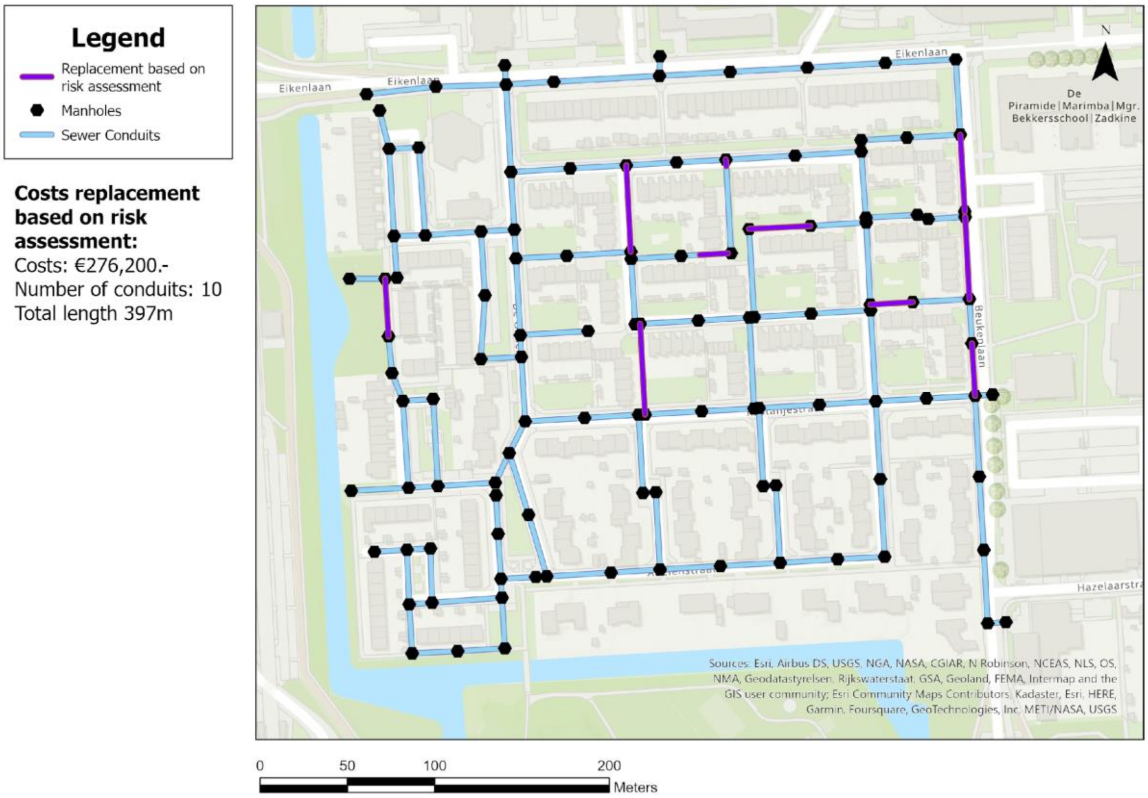

Figure 23. Risk-based rehabilitation scheme, with conduits needing replacement coloured in purple.

5.3.2 Example 2: Zuidland

The risk assessment and condition assessment of Zuidland shows a prominent difference. In Figure 24. red dominates the map in the north (see Figure 28), whilst in the risk assessment (Figure 26 and 29) the colour division is much more balanced. Figure shows a zoomed-in area of Zuidland, highlighted in Figures 28 & 29 with a red arrow. It gives insight in how the different levels of risk came about. Even though all three defects have the highest probability of failure (Intervene, once per /10 years), their consequence of failure is different. One defect has a high risk, due to its intersect with a low-pressure gas pipe (severity score of 4). One defects has a moderate risk, due to its intersect with a drinking water pipe (severity score of 3), and the third defect has a low risk. The low risk defect does not intersect any underground infrastructure, or any buildings. It is also not nearby a vulnerable building, and thus the largest impact of the sinkhole at that location is road damage, i.e. reduced accessibility. The damaged road is a residence road, with a severity score of 2, that gets damaged, thus resulting in only a low risk of failure.

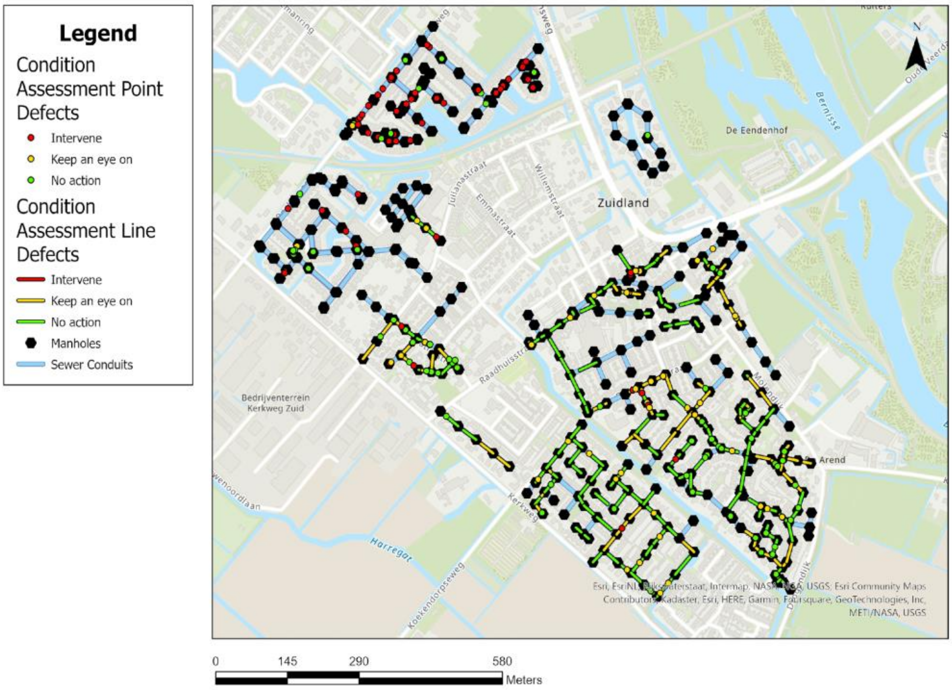

Figure 24. Condition assessment of defects in Zuidland.

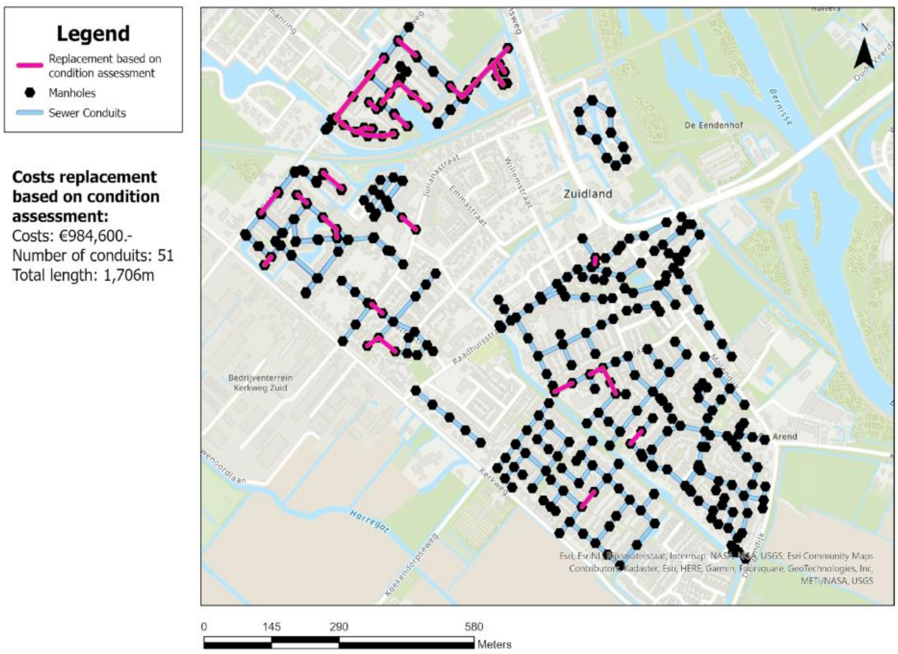

Figure 25. Rehabilitation scheme based on condition assessment.

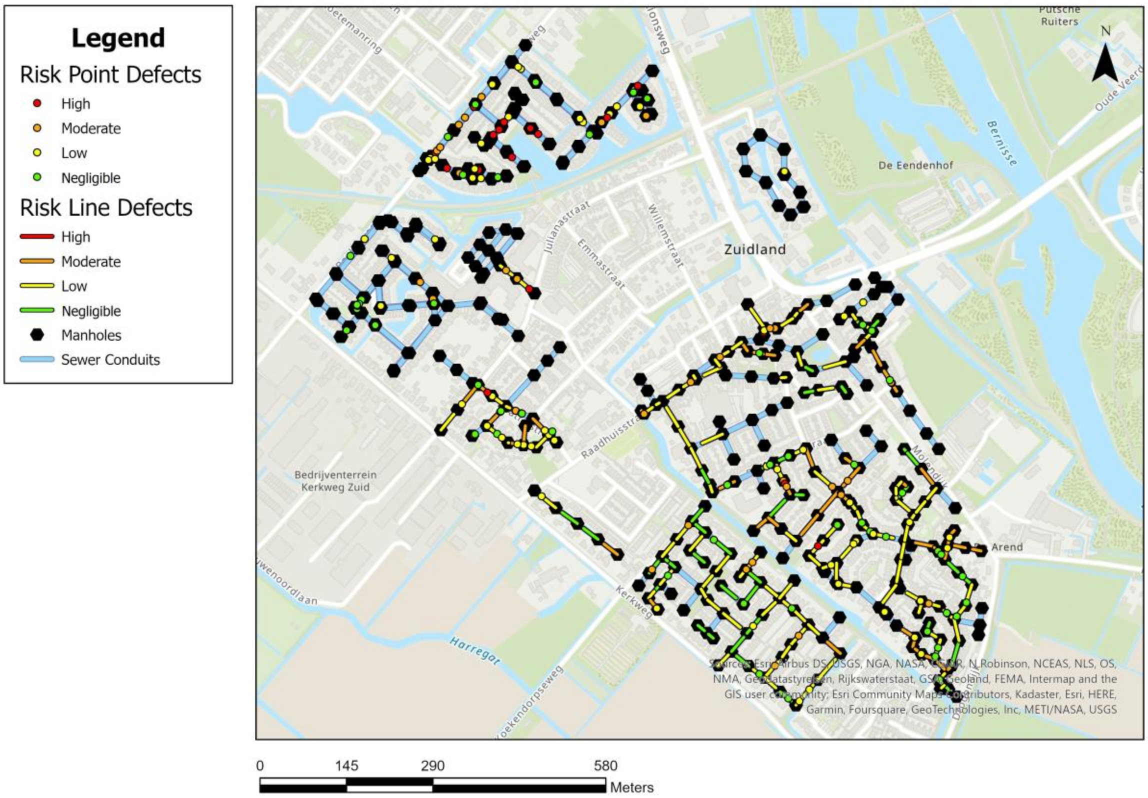

Figure 26. Risk assessment of defects in Zuidland.

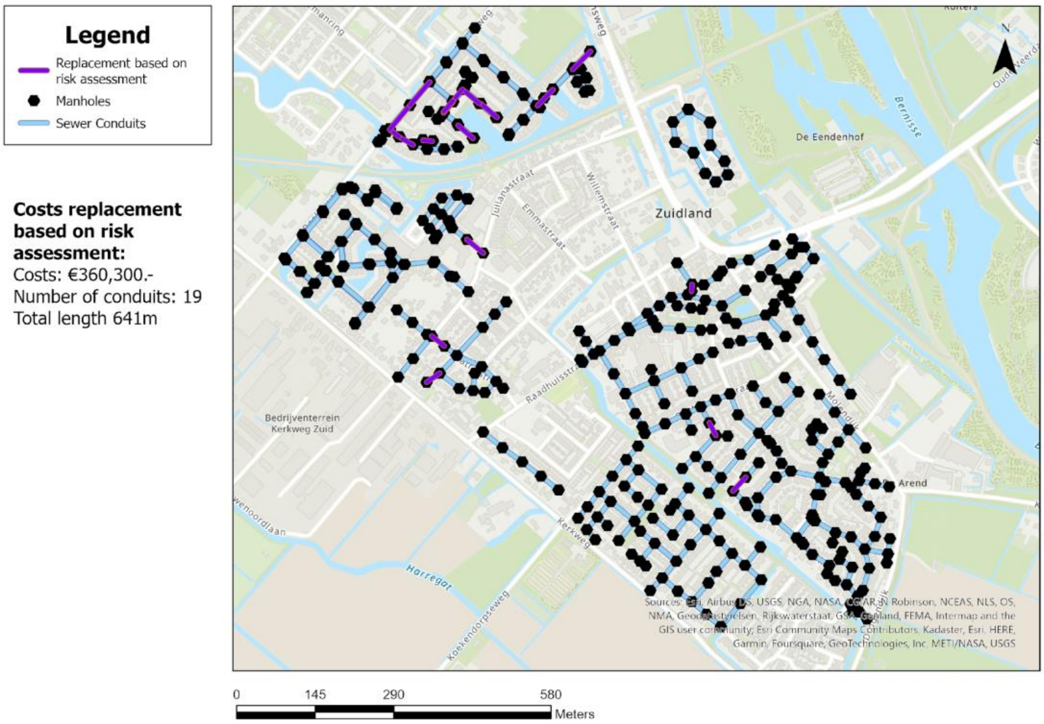

Figure 27. Replacement scheme based on risk in Zuidland.

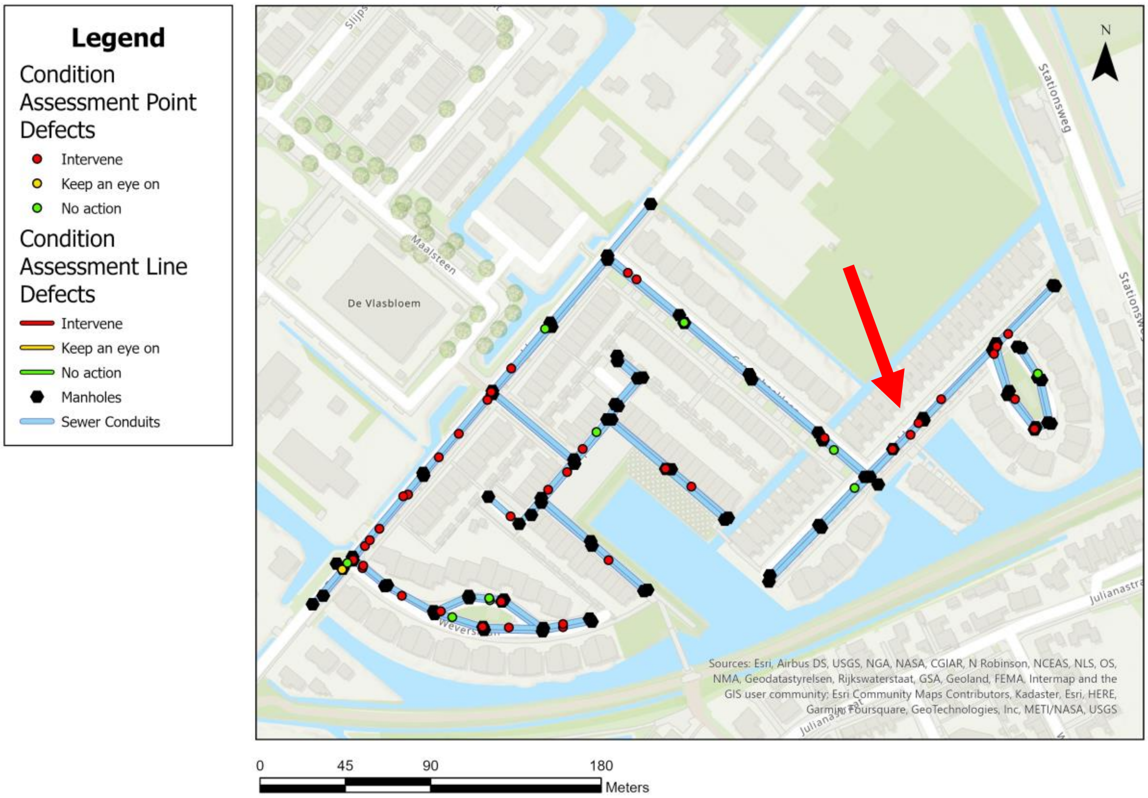

Figure 28. Sewer condition assessment of the northern region of Zuidland. The arrow indicates an area that is highlighted in Figure 24.

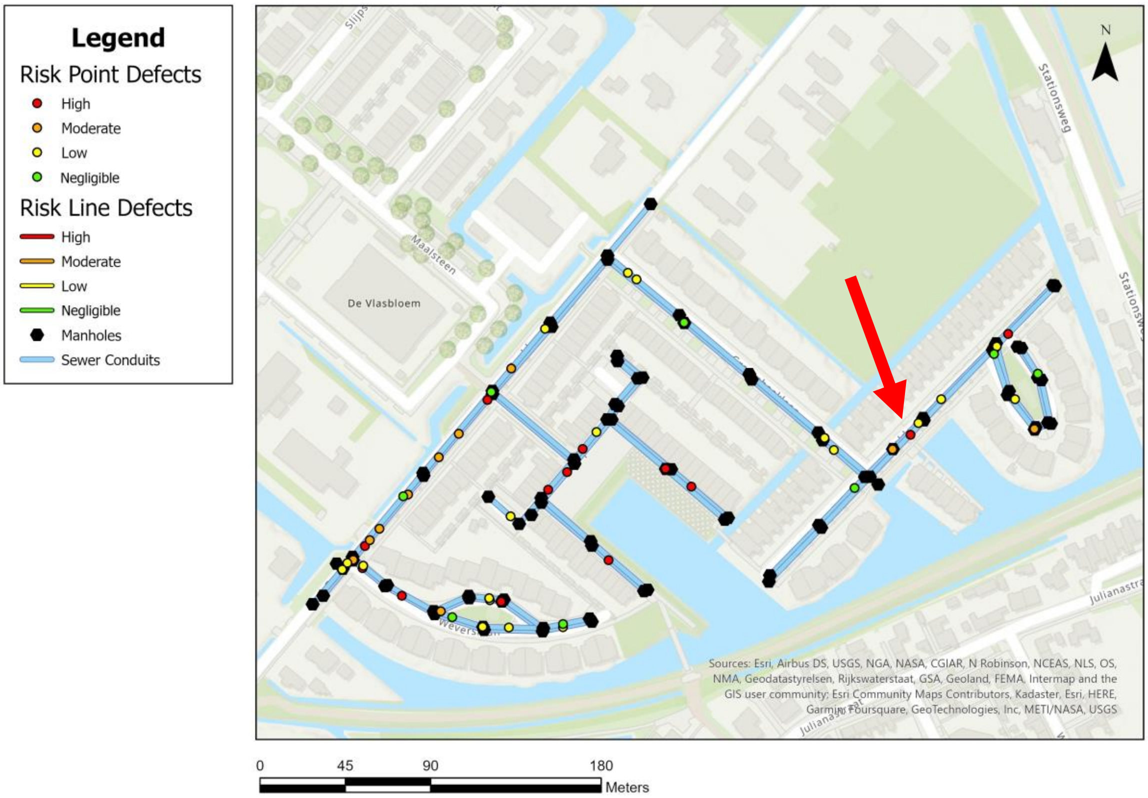

Figure 29. Risk assessment of the northern region of Zuidland. The arrow indicates a region that is highlighted in Figure 24.

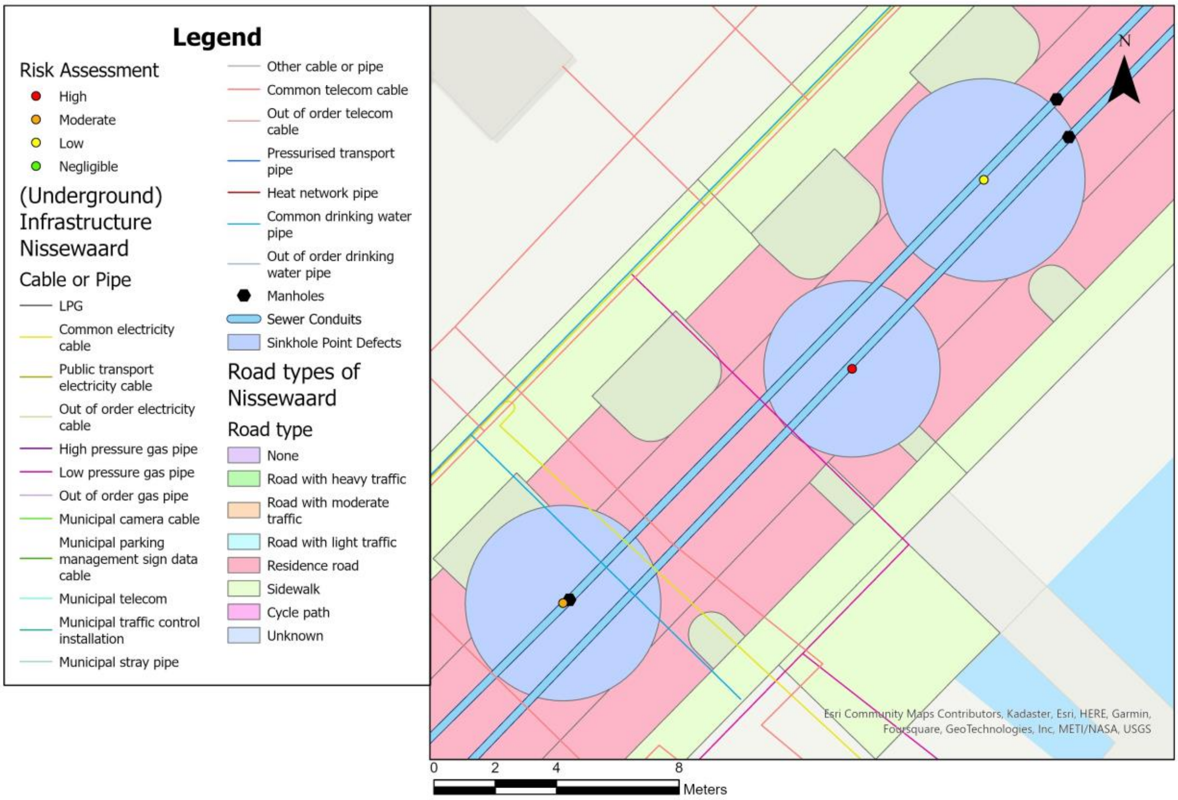

Figure 24. Three defects with a different risk assessment. The blue circles represent their sinkhole. The spatial context is given as well to provide insight in how the different risk levels came about.

Due to the high number of defects needing intervention, 51 conduits would need to be replaced according to the current asset management approach. This would require an investment of nearly a million euros. See Figure 25.

If the risk-based approach is applied, only 19 conduits need to be replaced. Figures 26 and 27 portray the risk assessment and its respective replacement scheme. The associated costs of risk-based sewer asset management in Zuidland are 360 thousand euros. The current asset management approach and risk-based asset management approach thus result in a significantly different rehabilitation plan, with a cost difference of 620 thousand euros. The efforts required for the risk-based approach are thus significantly lower.

5.3.2.1 Result of Conduit Replacement Zuidland

To study the remaining risk after conduit replacement, the risk of sewer collapse has been determined on the conduit level. The condition and risk assessment on the conduit level are shown in Figures 28 and 30 respectively. The efforts of rehabilitation on the level of risk in Zuidland are shown in Figures 29 and 31.

After replacing all sewer conduits with an ‘intervention’ label, 51 of the conduits have been given a label of ‘None’ for the remaining risk. Especially the northern area of Zuidland required a lot of replacement efforts, where all types of risk: negligible, low, moderate and high have been removed.

The risk-based strategy only entailed the removal of 19 conduits. Thus, fewer conduits have been changed to a risk of “None”. However, similarly to the current asset management replacement strategy, no ‘High-risk conduits remain.

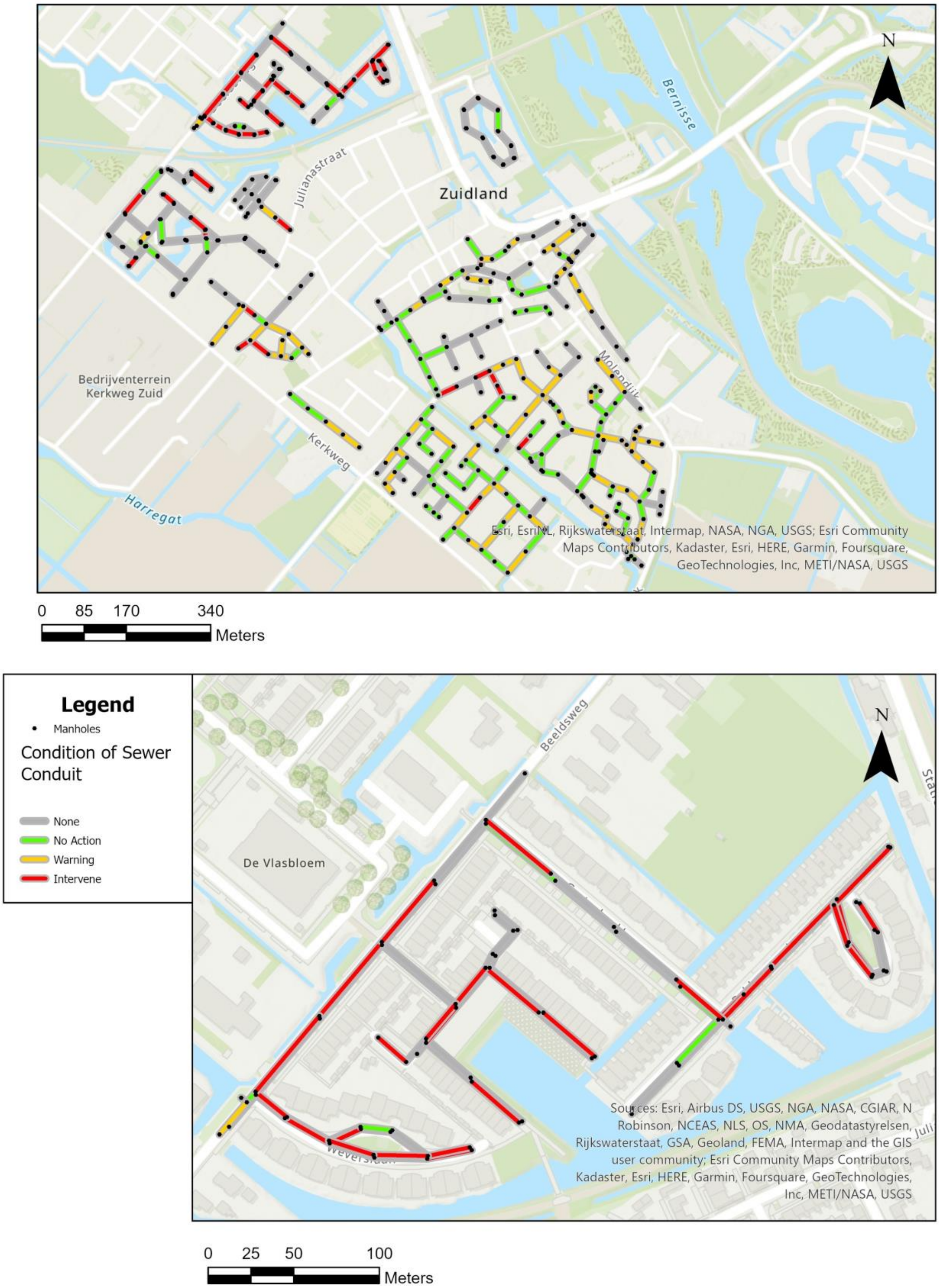

Figure 28. Condition assessment on conduit level in Zuidland.

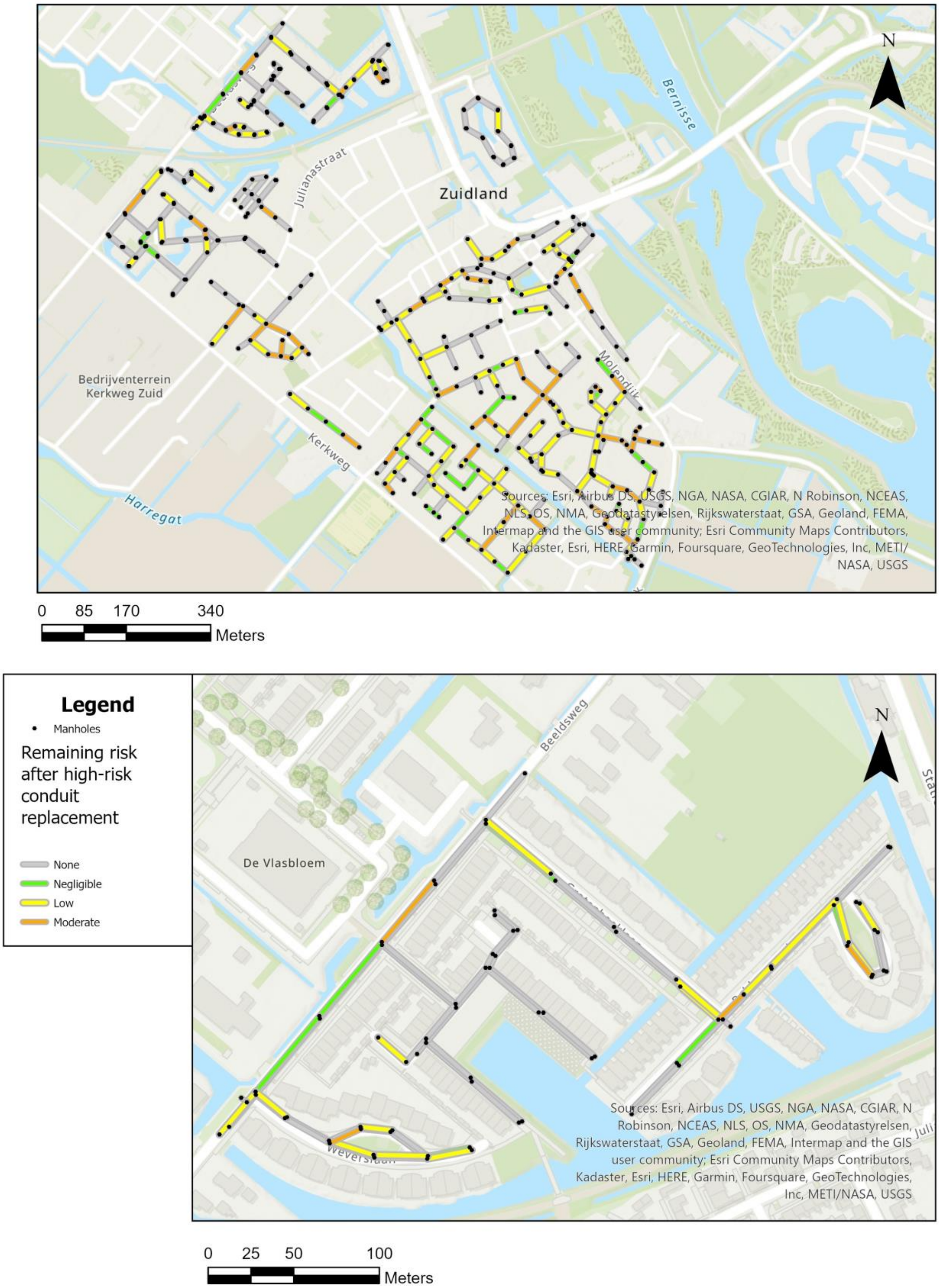

Figure 29. Risk on conduit level after replacing conduits with an intervention status.

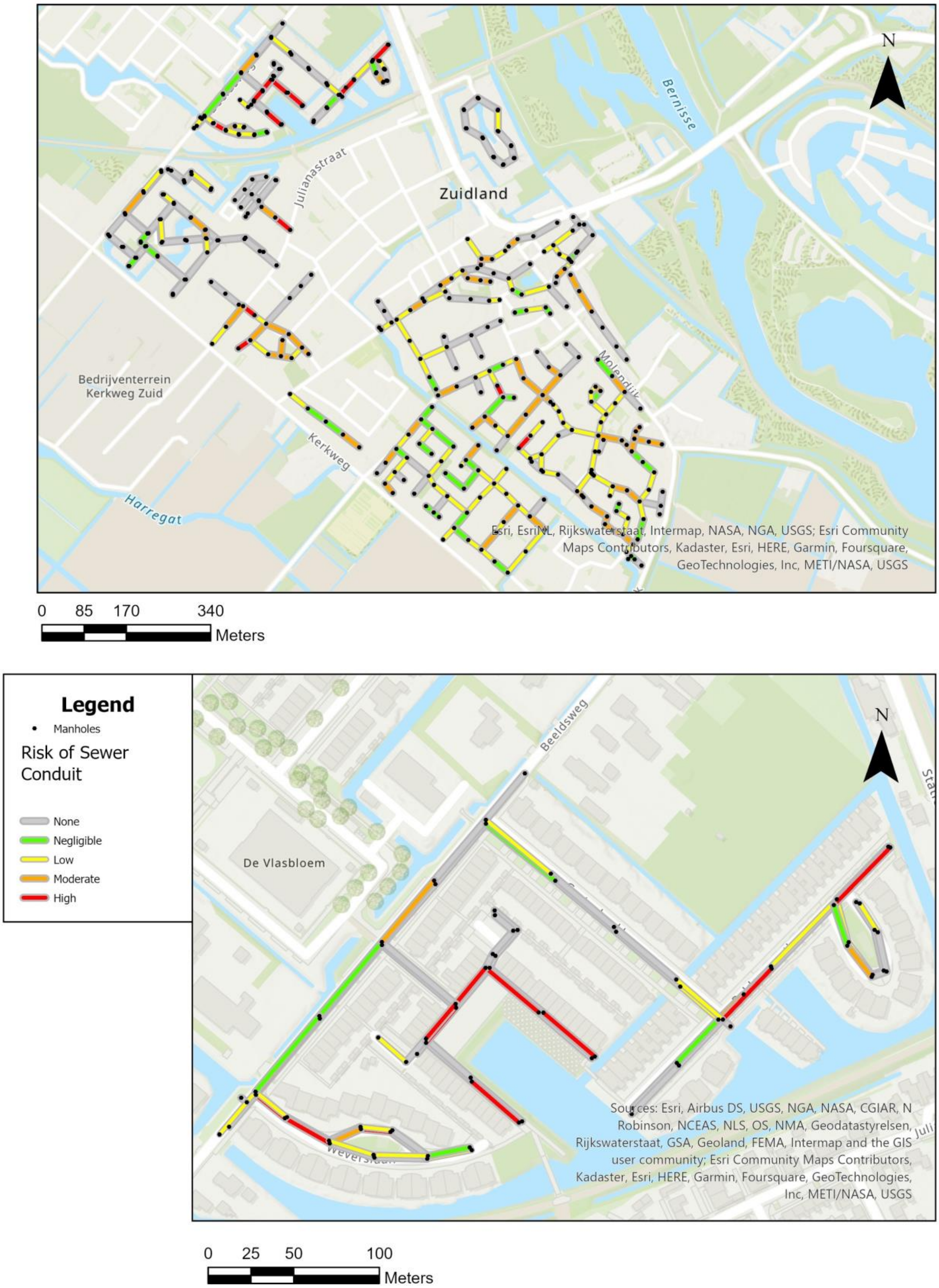

Figure 30. Risk of sewer collapse on conduit level in Zuidland.

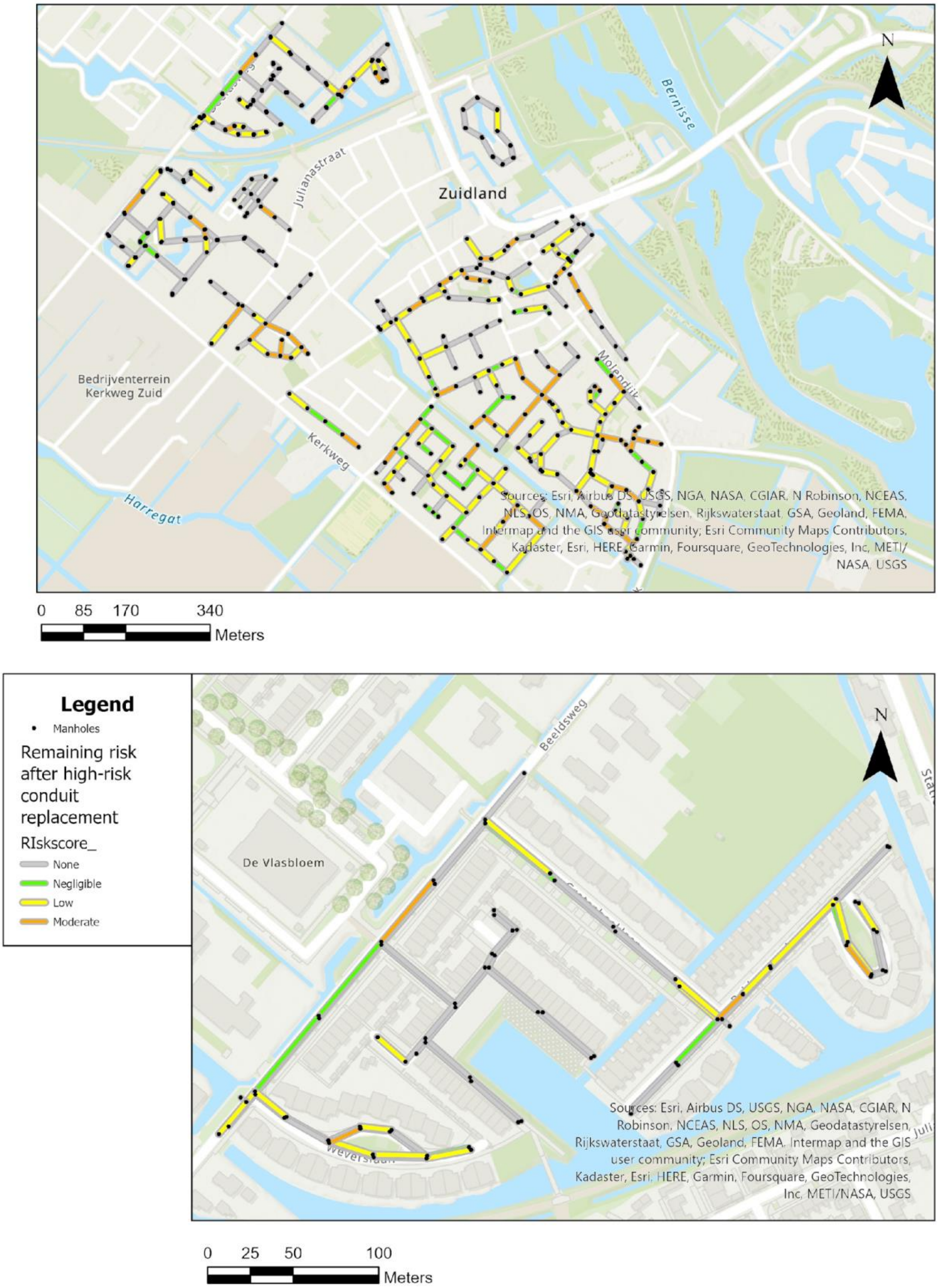

Figure 31. remaining risk of sewer collapse after replacing high-risk sewer conduits.

6 DISCUSSION

This chapter will discuss the key findings and provide an answer to the thesis question: "*How can the risk of sewer collapse be determined and what are its implications for sewer asset management?".* The interpretation and implications of the results will be discussed. Additionally, the limitations and validity of the research will be described together with topics for future research.

6.1 KEY FINDINGS

First, to reflect on the first part of the thesis question: "How can the risk of sewer collapse be determined?". This study has shown the risk can be determined by combining data from visual sewer inspections and geospatial layers, with a central role for the combined risk matrix. The severity of sewer collapse could be determined by using factors to assess the impact on the organizational values of a municipality. By making use of buffers to represent the potential sinkhole that could form due to a lack of stability, an overview of possible consequences is created. The probability of sewer failure is determined by making use of the current condition assessment as a proxy for the chance of sewer failure. The level of risk of a defect can help a municipality prioritize where rehabilitation efforts are required first.

In Nissewaard, the risk and condition analysis clearly showed a different perspective. Looking at defects that were coloured red on the condition assessment map, only slightly more than half remained red on the risk assessment map. Logically, the associated replacement strategies of both asset management styles differ.

The results show there is a significant cost and effort reduction when a risk-based sewer asset management approach is applied in Nissewaard. The costs of replacement were halved when only replacing high-risk conduits instead of 'intervention'-conduits. Even though the rehabilitation efforts are much more extensive for the current asset management approach, the results on the remaining level of risk are similar for both approaches. In both approaches, all high-risk conduits are replaced. For the current asset management replacement strategy, conduits with moderate, low or even negligible risk are also replaced. In the end, there is a one per cent difference for both moderate and low-risk conduits remaining for risk-based asset management compared to standard sewer asset management.

6.2 IMPLICATIONS OF RESULTS

At present, Stichting RIONED has only established guidelines outlining the principles and concepts underlying risk-based asset management, yet it lacks a comprehensive link to practical implementation. The conventional sewer asset management approach predominantly focusses on establishing the condition of a sewer as a basis for formulating rehabilitation strategies. This results in a somewhat ad-hoc methodology that leaves significant room for enhancement. In this context, transitioning to a risk-based asset management leads to a more informed and systematic decision-making scheme. The present study effectively addresses the need for a methodology that enables risk-based sewer asset management.

This study is also an extension of current research on risk assessments of sewer failure. Present studies often only study the direct surface area above a conduit (Salman & Salem, 2012; Lee et al., 2021; Vladeanu & Matthews, 2019; Baah et al., 2015). However, if a sewer collapses, a sinkhole is the expected result, which compromises a much larger area than only the surface above a conduit. If besides the direct area above the conduit, a larger area is analysed, this is often done by a seemingly arbitrary-sized buffer (Baah et al., 2015; Lee et al., 2021). For example, Baah et al. use a distance of 120m to assess the nearness of a hospital, 200m for a school, and 20m to a recreational park. Each of these so-called impact factors is attributed to a different performance value. It is stated that the distances and performance values are based on a literature review, but no further explanation is given as to how these distances or values came about. This thesis has focused on combining the efforts of Mekel (2020) to determine the consequence of sewer failure and sewer collapse risk analysis to attain a more precise assessment. By making use of a formula to determine the sinkhole in case of collapse, the affected area could be determined and analysed. This thesis thus enhanced the manner in which the COF of sewer collapse was determined for risk assessments.

The approach taken in this thesis to determine the probability of failure distinguishes it from previous research efforts. While many studies employ a sewer deterioration models for the POF assessment (Chugtai and Zayed 2008; Baik et al. 2006; Bauer and Herz 2002; Anbair et al., 2017, Salem & Salman et al., 2012, Vladeanu & Matthews, 2019), the present study employs a condition assessment based on visual sewer inspection. It is worth noting that the accuracy of deterioration models is often constrained and specific to particular locations (Tscheikner-Gratl et al., 2019; Aguilar-Lopez, in-press). In the Netherlands, visual inspections are conducted and evaluated following the standardized methodology outlined in NEN-EN 13508-2 (Stichting RIONED, 2019). The condition assessment is thus universal for the Netherlands, in contrast to the current sewer deterioration models. The thesis its methodology is thus suitable for the entirety of the Netherlands, and not limited to one municipality.

The incorporation of the combined risk matrix too contributes to its applicability across all municipalities in the Netherlands. While Stichting RIONED has described the role of the combined risk matrix for risk assessment, there is a lack of research applying this approach (Aberkrom et al., 2016). The use of the combined risk matrix allows for a comprehensive assessment of risk, aligning with the municipality's perspective. The results highlight the significance of considering the risk of sewer collapse, as it enables the identification of truly problematic defects requiring repair. This perspective is particularly valuable when faced with budget limitations, as resources can be allocated strategically to address high-risk defects rather than addressing all defects currently flagged as needing intervention.

Since, the worst possible consequence of sewer collapse is used to determine the risk, using the most relevant factor for determining the impact on an organizational value sufficed. Since, even though a factor may be relevant in assessing the impact on another organizational value, if the worst or similar consequence is already caused by another factor affecting that value, the overall outcome remains unchanged. In other words, considering multiple factors to determine the level of risk does not alter the result in such cases. The use of one factor to study the impact on one organizational value ensured the methodology remained easy to comprehend for a municipality. However, if an asset manager would like to give additional weight to a specific organizational value, it would be necessary to use all factors which are relevant to an organizational value and score them accordingly. The current methodology only allows steering rehabilitation based on the ‘general’ risk of sewer collapse.

To further compare the condition and risk assessment, one could argue that a negligible and low risk is comparable to the assessment of ‘no action’, a moderate risk is equal to a ‘warning’, and a high risk to ‘Intervene’. In other words, a high risk would lead to intervention, a moderate warning likely to additional supervision, and a low and negligible risk would not be given any special attention yet. When studying the distribution of risk within the condition assessment categories, it shows that for ‘no action’-defects, nothing changes. This is also to be expected, as the probability for collapse is so low, that the risk is too. For ‘Warning’-defects, three-quarters of the defects have been given a similar risk assessment. The remaining defects are for the majority categorized similarly to a 'No Action'-defect. Due to the small POF, the risk could never become high. Looking at 'Intervention'-defects, the difference is assessment is much more prominent. Only slightly more than half of them remain at the same level of risk. One-third of the 'Intervene-defects are given a risk label equal to 'No action', and only 10% to a 'Warning' level. Indicating that even though the POF is quite high, the severity of the consequences is low. In the context of sewer asset management in the Netherlands, there is a tendency to replace conduits prematurely due to the risk-averse nature of the population (Ferreira, 2018). However, adopting a more risk-informed approach could lead to improved resource allocation and cost-effectiveness. By waiting longer before replacing a conduit, there is a possibility that it could remain functional for an additional 10 years. Although there is a risk of the conduit eventually collapsing, the consequences can be calculated and managed. This approach not only optimizes cost efficiency but also promotes sustainability by prolonging the useful lifespan of resources and reducing waste. The remaining risk after both replacement strategies is quite similar, implying risk-based asset management offers a more cost-effective approach to rehabilitation. Embracing a certain level of risk allows for a better allocation of resources. It is uncertain if the occurrence of sinkholes would increase if a shift is a made to risk-based asset management. However, if the occurrence of sinkholes increases due to the acceptance of more risk, a beneficial side-effect might be an increased understanding of sewer deterioration processes and the consequences of collapse. Overall, risk-based asset management aims to optimize the trade-off between risk and cost, ensuring a more efficient and informed decision-making process.

In this study, a static risk assessment approach is utilized to determine the replacement strategy for sewer assets. However, it is crucial to recognize that the nature of risk is dynamic, meaning that the probability of failure changes over time. Defects that currently pose a moderate risk may escalate to a high-risk category as time progresses. Therefore, it is essential to closely monitor defects that are not immediately repaired, as their risk level may increase over time. It should be acknowledged that this research focuses solely on a static assessment and does not explore how risk should inform a long-term rehabilitation strategy. The risk should therefore purely be seen as a tool to prioritize sewer rehabilitation. Future studies should elaborate on how the dynamic nature of risk for sewer collapse can be incorporated and used to develop rehabilitation strategies. By incorporating time-dependent factors, such as deterioration rates and aging effects, more effective and proactive rehabilitation plans can be devised to address evolving risks in the sewer system.

6.2.1 Implications of the Case Study Area

The proposed methodology is tested on the sewers inspected between 2020-2023 in Nissewaard. This study makes use of shapefiles provided by the municipality of Nissewaard. To repeat the methodology, similar shapefiles would be required. It is unclear if every municipality has a similar database as Nissewaard. However, many open data sources could be used to create the same results. Regarding underground infrastructure, one can make use of the database of KLIC, which stores overviews of the underground infrastructure for every municipality (Kadaster, 2023). The "Nationaal Wegenbestand"(national road database) can be used for the analysis of the impact of a sinkhole on accessibility(Nationaal Wegenbestand, n.d.).

The BAG is an open data source which has been used for determining if a sinkhole overlaps with a building. Since the function of a building is listed in the BAG register, it can too be used to assess the closeness of a vulnerable building like a school or hospital. In addition, the risk contour map of Atlas Leefomgeving can be used to determine the vulnerability of the area. This map stores information on locations that store hazardous substances (Atlas Leefomgeving, n.d.). In case certain information is not available, the analyses should be slightly altered to fit the accessible data. Nevertheless, as described, there are many open data sources available to carry out a similar analysis for every municipality.

Nissewaard is considered representative of other Dutch urban areas, as it is relatively flat, and contains both newer and older build-up areas. Therefore, the case study allows one to test the methodology and compare its output and generalize its implications for the rest of the Netherlands.

Many municipalities do not have a business value risk matrix, as is also the case for Nissewaard. Either the risk matrix can be developed or the risk matrix of another, similar municipality can be taken.

6.3 Limitations & Opportunities for Future Research

The proposed methodology in its current form exhibits certain limitations when it comes to evaluating the failure probability. Instead of directly estimating failure probabilities, the approach relies on condition assessment as a surrogate measure for the likelihood of sewer collapse. However, it is essential to acknowledge the presence of considerable criticism concerning the prevailing condition assessment techniques (Tscheikner-Gratl et al., 2019). These techniques introduce subjectivity, as different experts may perceive defects and their severity levels differently. As a consequence, constructing a robust sewer deterioration model becomes challenging due to the subjective nature of the input data. To address this issue, a paradigm shift in inspection techniques is warranted. Presently, visual inspection methods dominate the field, but they are criticized for their susceptibility to bias (Tscheikner-Gratl et al., 2019). Alternatively, the utilization of ring laser scanning coupled with camera movement compensation methods emerges as a potential solution. This advanced technology enables the acquisition of detailed 3D geometry data, facilitating the measurement and localization of deformation, material loss, obstacle dimensions, and lateral connection intrusions (Clemens et al., 2014). Additionally, Ground Penetrating Radar can be used to detect significant ground voids, pipe collapses, and leaks, offering valuable insights (Hao et al., 2012). If these inspection techniques are applied, allowing for a more objective sewer condition assessment, the accuracy of sewer deterioration model is likely to improve. Then, the integration of a sewer deterioration model would enable a more accurate estimation of the remaining lifespan. Enhancing the study further would entail the development of a sewer deterioration model applicable to the entirety of the Netherlands to ensure the generalizability of the findings.

Further investigation is needed to explore the practical implementation of these techniques in the field. Achieving widespread adoption of these new methodologies may necessitate a paradigm shift in current practices. The integration of research findings into practical applications is often impeded by a lack of connection between academia and practice, thereby hindering the adoption of innovative approaches. Additionally, the resistance of sewer asset managers to embrace change and implement the proposed methodology presented in this study should not be overlooked. As highlighted by Pryjmachuk (1996), effecting change to address contemporary societal challenges requires not only epistemic, i.e. scientific knowledge but also practical knowledge. Regrettably, this crucial need for practical knowledge is often disregarded by academic researchers, resulting in a disconnect between theoretical frameworks and practical implementation. To bridge this gap between academia and practice, it is essential to study what changes are required for the successful implementation of new sewer inspection techniques and risk-based asset management approaches

(Sharpe et al., 2016). Such research would serve as a vital next step in facilitating the necessary change and transformation needed in the field of conventional sewer asset management.

One limitation of the proposed methodology for determining the consequence of failure lies in its binary nature, which considers only the presence or absence of a spatial element within a buffer. This binary approach fails to capture the complexity involved in estimating the size of a sinkhole, as it relies on multiple inputs and data sources, making it susceptible to minor errors. Consequently, the actual size of a sinkhole may differ from the estimated size, leading to discrepancies in identifying the damaged spatial elements. Moreover, the assumption that all elements within a sinkhole will be uniformly affected may not hold true. For instance, while a nearby pipe is assumed to be damaged, it may remain intact. To address this issue, introducing a more nuanced scoring system with gradations in the level of effect could be beneficial. For example, using a secondary buffer with the inner ring representing the sinkhole and an additional buffer with a larger radius to deal with the uncertainty of the sinkhole size would allow for a more gradual attribution of scores.

Furthermore, the determination of the consequence of failure also does not consider the type of paving. Sinkhole collapses can be unpredictable and sudden as well as slow with warning signs (Kohl, 2001). This could be in the form of cracking of the surface or local subsidence (Sean, 2019). The type of paving (e.g. asphalt, tiles etc.) influences the nature of sinkhole formation, i.e. sudden or predictable. This fact was not considered for the analysis and provides a window of opportunity to improve the risk assessment of this study.

Additionally, the determination of the Consequence of Failure (COF) is based on the assumption that the highest potential effect level determines the overall risk. However, this assumption may not hold in reality, as the accessibility of a road may not be significantly affected by a sinkhole that primarily impacts a sidewalk. Assessing the actual damage of a collapsed line defect is even more challenging, as it is unclear where a conduit will fail if damages extend along its length. Therefore, the risk level of a line defect relies on the assumption that the risk is as high as the most problematic sinkhole. It would be valuable to assess the uncertainty associated with the current risk assessment of line defects. Besides the uncertainty regarding the location of collapse, the estimated effect level and the actual damage caused by sinkholes too remain uncertain. Sinkholes are relatively rare occurrences and their registration is limited. Municipalities often hesitate to report sewer collapses to avoid public commotion (Personal communication R. van Alphen; Stichting RIONED, 2021b). Consequently, the true extent of the damage caused by sinkholes, such as the impact on nearby structures, remains unknown. In Nissewaard, damage to underground infrastructure was identified as a significant risk factor. The existing sewer asset management practices typically involve interventions before a sewer collapses, which limits our knowledge regarding the realistic damage to underground infrastructure resulting from such collapses. As a consequence of this proactive approach, there is a lack of comprehensive understanding regarding the actual impact of sewer collapses on the underground infrastructure. Similarly, the overall area that is impact by a sewer collapse is not known. The use of a 10-meter radius to assess vulnerability is common in studies, but its appropriateness requires further investigation. Future research should aim to determine a more accurate radius of effect and address the limitations and uncertainties associated with sinkhole damage assessment.

One notable advantage of the practical methodology presented in this research is its potential for generalizability, as it can be applied to all municipalise that possess inspection data, regardless of the project’s scale. Consequently, the significance of individual conduits with the overall sewer network have not been taken into account. A hydraulic model is required to determine the significance of an individual conduit, which is not scalable for larger study areas. The failure of a conduit could not only have detrimental effects on the socio-economic environment surrounding the location of failure but also on the entirety of the sewer network. In order to assess the criticality of conduits within the network, the utilization of a hydraulic model, such as the implementation of Graph-theory (Meijer et al., 2018), is recommended. This approach employs a digraph representation of the sewer system, with manholes as nodes and conduits as links, allowing for the identification of all feasible water flow routes and their associated costs, specifically the distances that need to be traversed. Integrating the determination of conduit criticality into the analysis would introduce an additional dimension to the assessment of sewer failure risk. However, such models are not scalable yet and require a substantial amount of data, which might not always be present (Meijer et al., 2018). Consequently, the consideration of sewer conduit criticality has been excluded from the methodology to ensure its simplicity, scalability, and adaptability to meet the objectives of different municipalities.

Lastly, it is important to highlight that this study exclusively focuses on the risk of sewer collapse, while other failure mechanisms, such as loss of water tightness and hydraulic capacity, have not been taken into account. Since sewer collapse is typically considered more problematic than hydraulic sewer failure due to its potential for severe consequences on both the immediate surroundings and the entire sewer network. While hydraulic sewer failure, such as loss of water tightness or hydraulic capacity, can lead to localized flooding and operational challenges, sewer collapse involves the physical collapse or failure of a sewer pipe, resulting in more significant disruptions and risks. When a sewer pipe collapses, it can lead to extensive damage to the surrounding infrastructure, including roads, buildings, and utility systems. The resulting sinkholes or depressions pose significant safety hazards and can cause property damage or even injury to individuals in the vicinity (Kuliczkowska, 2016). However, to provide a comprehensive overview of the risk associated with all sewer failure mechanisms, it is necessary to incorporate additional spatial factors into the analysis. The thesis of Mekel (2020) describes a methodology for analysing the consequences associated with hydraulic sewer failure. Mekel's work could provide a foundation for developing an risk analysis applicable for all sewer failure mechanisms.

7 CONCLUSION

To conclude, this thesis has developed a methodology to assess the level of risk of structural sewer failure using the combined risk matrix as a framework. The risk of sewer collapse can be determined by using visual inspection data to estimate the probability of sewer collapse and geospatial factors to assess the consequences. The visual inspections of a sewer were translated to a condition assessment to relate the defect to a chance of sewer collapse. Since the condition assessment has been standardized in the Netherlands, all municipalities can assess the probability of failure of sewer collapse. Factors were chosen in such a way that the consequence of sewer collapse on organizational values can be assessed. In this study, the impact on the organizational values: safety, finance, accessibility and reputation was analysed by studying the damage to/or nearby underground infrastructure, buildings, roads and vulnerable buildings respectively. By combining the COF and POF of sewer collapse using the combined risk matrix as a framework, the risk of sewer collapse could be determined for sewer defects and conduits. The risk of sewer collapse should be used as an additional aspect to inform a sewer rehabilitation schedule. In other words, the developed methodology allows for the implementation of risk-based sewer asset management in the Netherlands.

The methodology is suitable for widespread implementation in the Netherlands due to its flexible and scalable nature and the use of widely available data. The study addresses the need for a practical roadmap on how to implement risk-based sewer asset management. Moreover, it elaborates on previous research by making the contextual assessment of a defect more precise to the area that is affected in case of structural sewer failure. Instead of only studying the direct area above a conduit, sinkholes were used instead. This thesis has combined the efforts of studies focusing on risk determination and consequence determination to create a more comprehensive risk assessment. Additionally, in contrast to previous research, the methodology applied the combined risk matrix as advocated by Stichting RIONED to determine the level of risk of sewer collapse. Thereby facilitating the research organization with an illustrative example of how to implement their theoretical guidelines for assessing the risk of sewer failure. The use of the risk matrix ensured the perception of risk of the municipality was captured in the risk assessment.

The findings derived from this study provide compelling evidence that risk-based asset management can enhance the resource allocation for maintaining sewer systems. The application of this approach improves the cost-effectiveness of spendings by municipalities by targeting resources toward mitigating the risk of sewer collapse. In contrast to the conventional replacement strategy, where all conduits labelled as needing intervention, irrespective of their risk, are replaced. By selectively replacing only those conduits that exhibit a significant risk, the risk-based asset management approach potentially allows for an extended lifespan of conduits, thereby enhancing the overall useful lifespan of these resources. Consequently, the adoption of risk-based asset management offers an opportunity to optimize resource allocation by incorporating risk as an additional criterion alongside cost considerations and the condition assessment.

However, it should be noted that this study is only signifies the first step of using risk to inform sewer rehabilitation. To improve the understanding of the role of risk in informing long-term rehabilitation strategies within the field of risk-based asset management, further research efforts should focus on investigating how risk assessment can effectively capture the dynamic nature of risk. By improving the understanding of risk, and its dynamic nature, resource allocation and prioritization is expected to be enhanced a well. In other words, a more comprehensive risk analysis has potential to facilitate an improved efficiency and effectiveness of managing sewer systems.

Additionally, to further enhance the robustness of this study, the development of a sewer deterioration model specifically tailored for the context of the Netherlands is recommended. This model would serve as a replacement for the current reliance on the condition assessment as a proxy for estimating the probability of sewer collapse. Moreover, the possibilities to improve the objectivity of sewer inspections should be explored and implemented. The options for improving this study provide a valuable opportunity to synergize the efforts of the aforementioned research fields. By integrating the newly acquired inspection data into the sewer deterioration model, the accuracy of estimating the probability of failure might improve. This integrated approach would enable a more robust analysis of risk and aids in the development of proactive maintenance and rehabilitation strategies for sewer infrastructure.

This study has bridged the gap between academia and practice, by creating a straightforward methodology, which integrates the guidelines of Stichting RIONED and incorporates the theoretical insights from various risk assessment studies. The outcome is a scalable and flexible risk assessment approach for sewer collapse that can be readily adopted by municipalities throughout the Netherlands. Nevertheless, given the potential resistance to change among practitioners in sewer asset management, it is advisable to conduct a supplementary study that specifically addresses the obstacles associated with implementing risk-based asset management and offers strategies to overcome them.

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9 APPENDIX

9.1 DESCRIPTION FME

Feature Manipulation Engine (FME) is a software tool that can manipulate over 400 different data formats (*FME | Esri Nederland*, n.d.). It supports conversions, data validation and transformations. A user can create a workflow that automates the manipulation of data. Below is an example of an FME script that has been developed for the purpose of this study.

Figure 32. Example of FME script.

9.2 DATA PROCESSING RIBX TO SHAPEFILE

In order to carry out the spatial analysis it was necessary to transform the inspection data to a shapefile. The inspection data was stored in a RibX which is conform the GWSW-rib information model. This is a model that stores all definitions and relations regarding defects as well as the maintenance of conduits, manholes, and churnings of a gravity sewer. The manner in which information is stored is conform the NEN-EN 13508-2. This standard has been created to allows an easy exchange between municipalities and companies.

In a RibX one can find the information on coordinates of the manholes as well as their depth in relation to NAP. Additionally, the ribx includes information, but not limited to, regarding the diameter, material and age of the sewer segments. For each segment, there is a summation of all present defects containing characteristics of the defect which are required to determine the class of a defect. For example, surface damage has a typing, e.g. increased surface roughness and a cause, e.g. mechanic, chemical, etc. Some defects also include a quantification, e.g. for a deformation the percentage of deformation is also registered. This information was then used to determine the class of a defect by linking it to an excel called classificatiemethodiek, which is a document made by Stichting Rioned based on the NEN-EN 13508-2 (2019) which links defects to a certain class (1-5) to represent the level of severity of the defect (Stichting Rioned, 2019). Then using dTabSb.BOR the sewer defect and its class are linked to a corresponding intervention measure and defect class. This document is used internally at Sweco, and reflects the general opinion of municipalities on what actions should be taken considering a certain defect.

Using the dTabSb.BOR, every defect is assigned either an N (no action required), W (warning, keep an eye on), (I) intervention required. Moreover, the same document was used to establish the type of sewer failure, i.e. loss of stability, watertightness or capacity.

In a RibX, for each defect the distance of the defect in respect to the manhole the inspection vehicle started from is noted. As the coordinates of the defect are not directly present in the data, this information needed to be established by making use of the coordinates of the manholes and the distance of the defect in respect to a manhole. To achieve this, first the bearing between two coordinates is calculated using the following formula:

$$\theta = atan2(sin(\Delta long).cos(lat2), \quad cos(lat1).sin(lat2) - \quad sin(lat1).cos(lat2).cos(\Delta long))$$

With:

$$\begin{aligned}&\theta = \text{bearing } [°]\\&\Delta\text{long} = \text{longitude point 2} - \text{longitude point 1 } [°]\\&\text{lat1} = \text{lattitude point 1 } [°]\\&\text{lat2} = \text{lattitude point 2 } [°]\end{aligned}$$

Then using the python package GeoPy, specifically geopy.distance, the coordinates of a defect is calculated. The function makes use of the coordinates of the manholes, the bearing and the distance of the defect to the manhole it left from. The GeoPy package makes use of the geodesic distance, which is the shortest distance on an ellipsoidal model of the earth along its surface (GeoPy Contributors, 2018).

The same was true for the depths of the defects, as only the depth of manholes were known. The depth of a defect was calculated by calculating the slope between two manholes:

$$\Delta = \frac{d_2 - d_1}{s}$$

With:

$$\begin{aligned}&\Delta\text{: the slope } \left[\frac{\text{m}}{\text{m}}\right]\\&\text{d2 : the depth of manhole 2 [m]}\\&\text{d1: the depth of manhole 1 [m]}\\&\text{s : the distance from the defect to manhole 1 [m]}\end{aligned}$$

Then using the slope, and the distance of the defect to manhole, the depth of the defect could be calculated.

$$Defect\ Depth\ [m] = s \cdot \Delta\ + d1$$

An additional distinction is made between "point" and "line" defects, i.e. some defects occur on a single point in the sewer segment, for example an axial crack, whilst other stretch over the length of the sewer segment, e.g. surface damage or a longitudinal tear. For the line defects, the starting point and ending point were noted as the distance from the manhole the camera left from, and both these distances were converted into coordinates to create a line that stretched between the coordinates of the starting and end point. However, as a line defect stretches over a sewer segment, it also has a variable depth, therefore the depth of the defect was taken as the average between the starting and end point of the line defect.

After determining the depth and coordinates of every defect, a shapefile can be constructed to visualize the sewer network including the sewer segments, manholes and defects (both lines and points). The entire process of translating a RibX to create a shapefile of the network and its defects is given in figure x. As this research only focuses on stability defects, a selection was made using an FME script to only keep the stability defects. Table 21 shows an overview of the present stability defects that were in Nissewaard based on the dTabSb.BOR. Not all stability defects were encountered in Nissewaard, e.g., collapse (BAC) or welding errors (BAM).

Table 21. Stability Defects present in Nissewaard.

Point stability defects	Line stability defects
• Defective repair	• Surface damage (e.g. chemical)
• Deformation	• Crack (in length)
• Defective Lining	
• Missing mortar	
• Surface damage (plugged-in inlet)	
• Crack (e.g. axial)	

9.2.1.1 Point and Line Defects

The distinction between a “point” and “line” defect could be made using the standard documentation of inspection data. A RibX-file is used to register the defects an inspector recognizes (Stichting RIONED, 2020c). It has a specific structure to document the NEN-codes of the defects. Figure 33 shows an example of how a defect, in this case, an ingrown root with code BBA, and its characterization in stored within a RibX. If a defect stretches over the conduit, the <J> is used to indicate a start and end position, using the letter A-C to indicate a start (A), end (B) or change of characterisation of the same defect (C) and a number to be able to create sets. To elaborate, within a conduit, there can be multiple continuous defects, therefore a number is assigned to keep track of which start and end position belong together. The <I> gives the distance from the defect to the manhole the inspection device left from. Figure 34 provides an example of defects within a conduit. It shows a continuous surface damage (BAF), which changes characterisation at 17.40m. It also shows a location with soil infiltration (BBD).

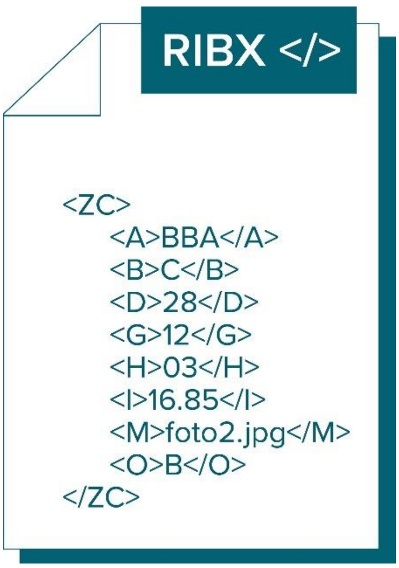


Figure 33. Observation of defect in RibX format (Stichting RIONED, 2020c).

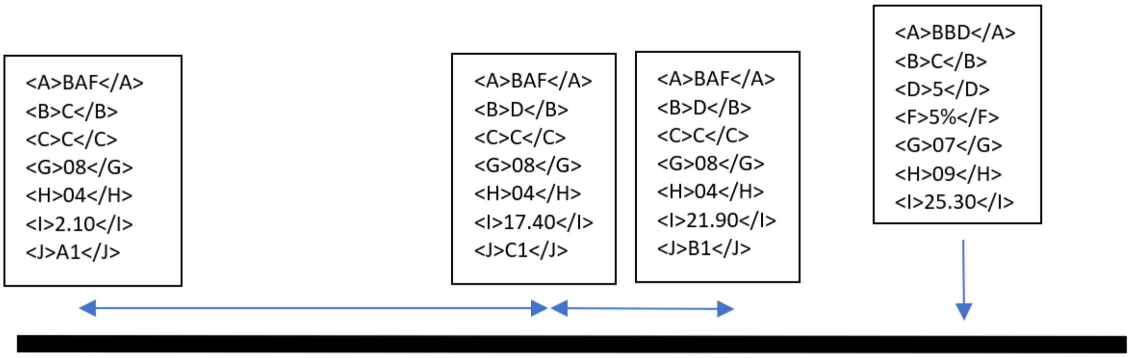


Figure 34. Example of Conduit with a continuous defect (line defect) and a point defect as registered in a RibX. The line defects are shown as a two-sided arrow which stretches over the conduit.

9.3 Workflow of RibX to Shapefile

The manner in which information was retrieved from the inspection data and projected into a shapefile is visualised in Figure 35.

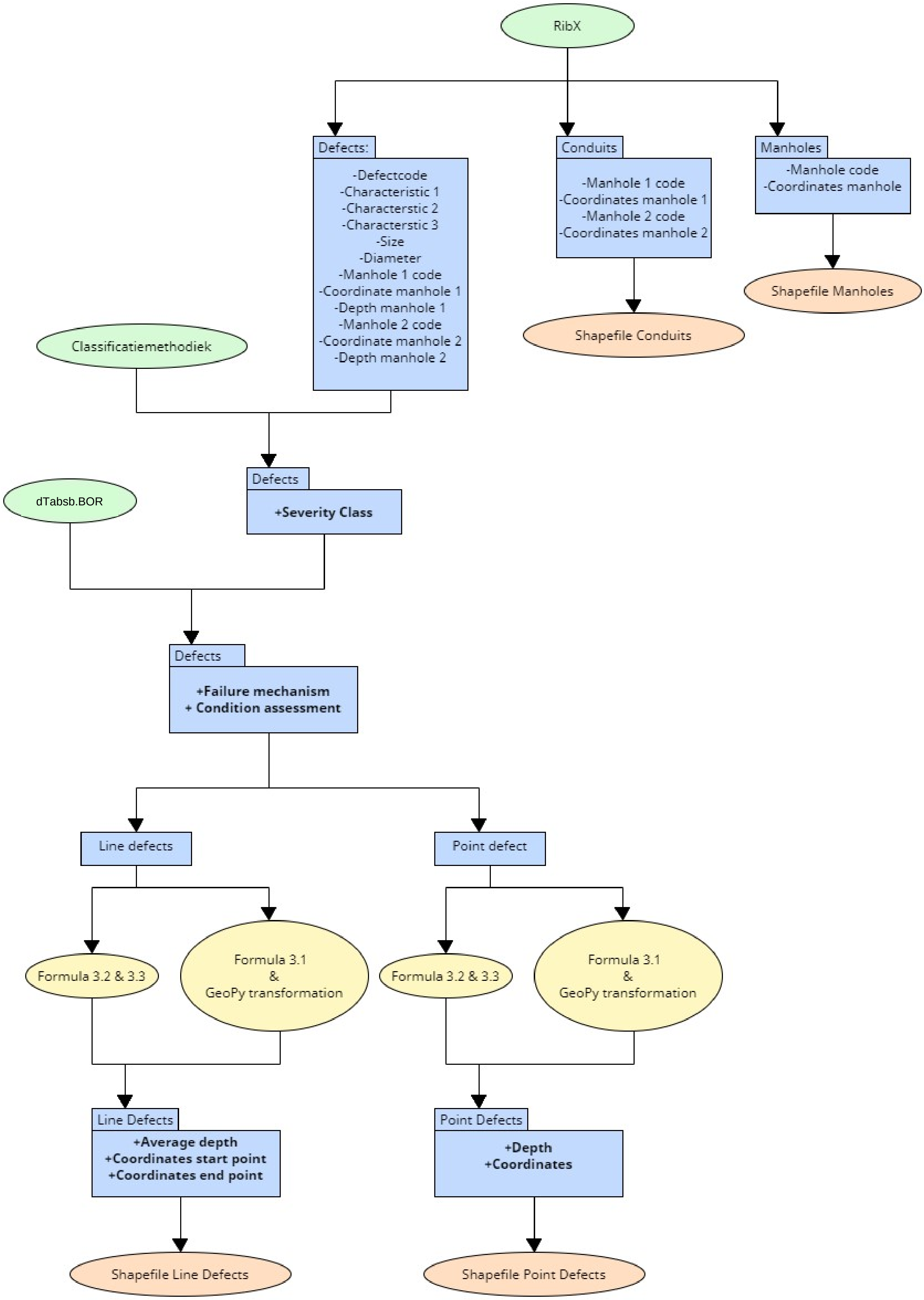

RibX
Defects:
-Defectcode
-Characteristic 1
-Characterstic 2
-Characterstic 3
-Size
-Diameter
-Manhole 1 code
-Coordinate manhole 1
-Depth manhole 1
-Manhole 2 code
-Coordinate manhole 2
-Depth manhole 2
Conduits
-Manhole 1 code
-Coordinates manhole 1
-Manhole 2 code
-Coordinates manhole 2
Manholes
-Manhole code
-Coordinates manhole
Shapefile Manholes
Shapefile Conduits
Classificatiemethodiek
Defects
+Severity Class
dTabsb.BOR
Defects
+Failure mechanism
+ Condition assessment
Line defects
Point defect
Formula 3.2 & 3.3
Formula 3.1
&
GeoPy transformation
Formula 3.2 & 3.3
Formula 3.1
&
GeoPy transformation
Line Defects
+Average depth
+Coordinates start point
+Coordinates end point
Point Defects
+Depth
+Coordinates
Shapefile Line Defects
Shapefile Point Defects

Figure 35. Workflow of RibX to Shapefile

9.4 EXAMPLE CONDITION ASSESSMENT

Figure x shows how the condition and failure mechanisms is determined for a defect. It starts with the information found in the RibX. Using the characteristics and quantification of a defect, the (severity) of a defect can be found using the document of Stichting RIONED: classificatiemethodiek. Now that the class of a defect is known, the needed intervention measure can be found (I: Intervene, W: Warning, N: No action). Additionally, the failure mechanism of a defect can be found in the dTabSb.BOR: the internal document of Sweco that links defects to an intervention measure.

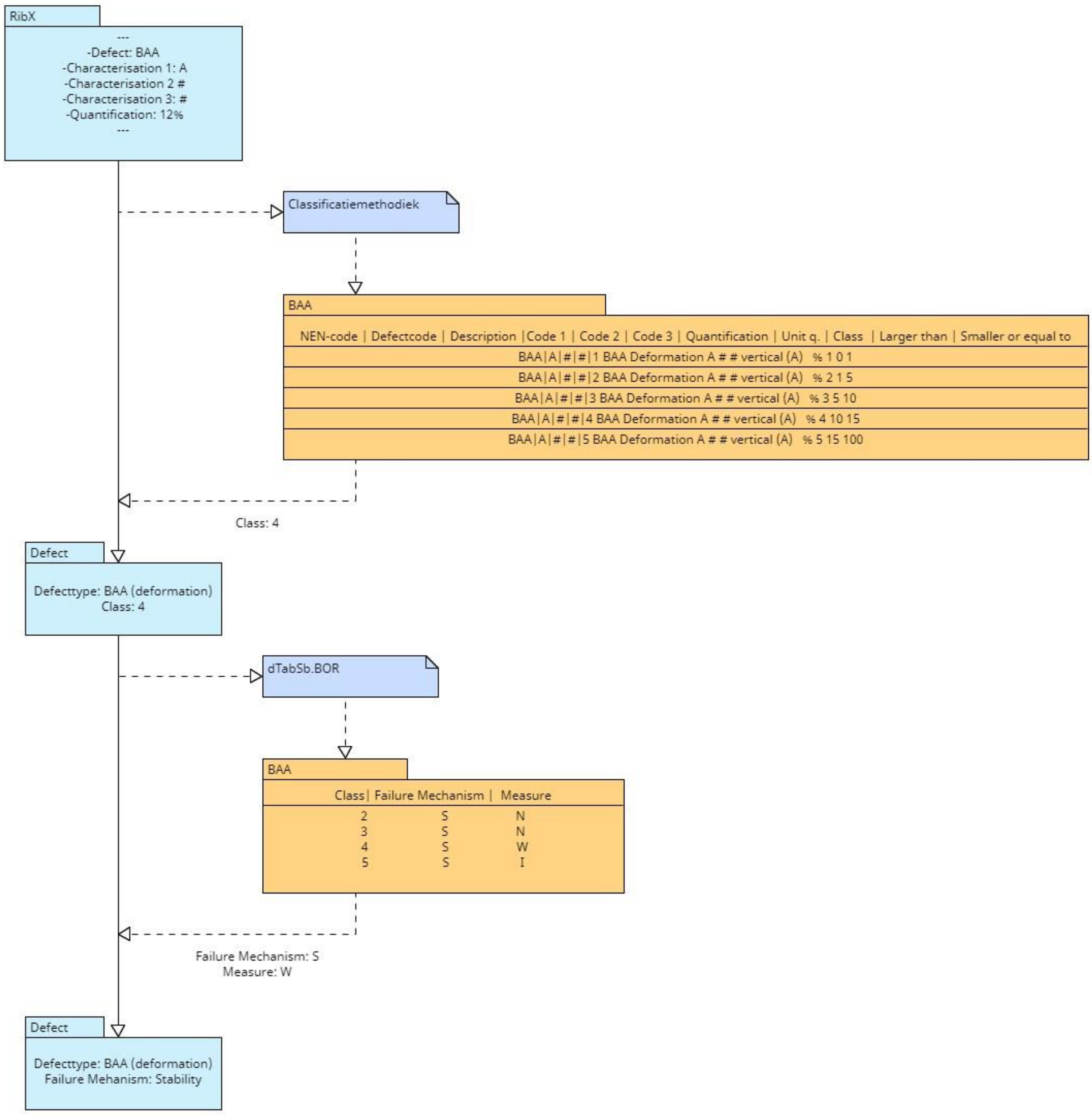
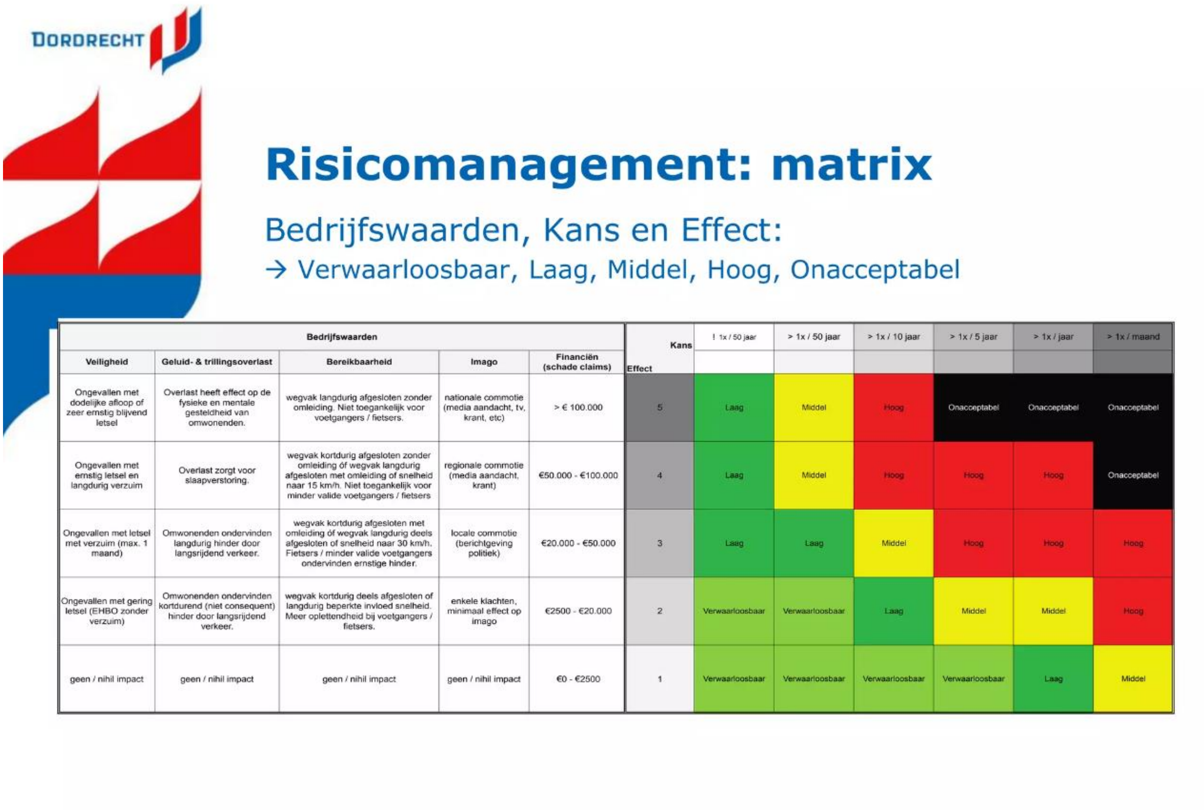


Figure 36. Illustration of the processing of a defect determine its condition.

9.5 Combined Risk Matrix of Dordrecht

Figure 37 shows the unaltered and non-translated combined risk matrix of Dordrecht.



Bedrijfswaarden					Kans / Effect	! 1x / 50 jaar	> 1x / 50 jaar	> 1x / 10 jaar	> 1x / 5 jaar	> 1x / jaar	> 1x / maand
Veiligheid	Geluid- & trillingsoverlast	Bereikbaarheid	Imago	Financiën (schade claims)							
Ongevallen met dodelijke afloop of zeer ernstig blijvend letsel	Overlast heeft effect op de fysieke en mentale gesteldheid van omwonenden.	wegvak langdurig afgesloten zonder omleiding. Niet toegankelijk voor voetgangers / fietsers.	nationale commotie (media aandacht, tv, krant, etc)	> € 100.000	5	Laag	Middel	Hoog	Onacceptabel	Onacceptabel	Onacceptabel
Ongevallen met ernstig letsel en langdurig verzuim	Overlast zorgt voor slaapverstoring.	wegvak kortdurig afgesloten zonder omleiding óf wegvak langdurig afgesloten met omleiding of snelheid naar 15 km/h. Niet toegankelijk voor minder valide voetgangers / fietsers	regionale commotie (media aandacht, krant)	€50.000 - €100.000	4	Laag	Middel	Hoog	Hoog	Hoog	Onacceptabel
Ongevallen met letsel met verzuim (max. 1 maand)	Omwonenden ondervinden langdurig hinder door langsrijdend verkeer.	wegvak kortdurig afgesloten met omleiding óf wegvak langdurig deels afgesloten of snelheid naar 30 km/h. Fietsers / minder valide voetgangers ondervinden ernstige hinder.	locale commotie (berichtgeving politiek)	€20.000 - €50.000	3	Laag	Laag	Middel	Hoog	Hoog	Hoog
Ongevallen met gering letsel (EHBO zonder verzuim)	Omwonenden ondervinden kortdurend (niet consequent) hinder door langsrijdend verkeer.	wegvak kortdurig deels afgesloten of langdurig beperkte invloed snelheid. Meer oplettendheid bij voetgangers / fietsers.	enkele klachten, minimaal effect op imago	€2500 - €20.000	2	Verwaarloosbaar	Verwaarloosbaar	Laag	Middel	Middel	Hoog
geen / nihil impact	geen / nihil impact	geen / nihil impact	geen / nihil impact	€0 - €2500	1	Verwaarloosbaar	Verwaarloosbaar	Verwaarloosbaar	Verwaarloosbaar	Laag	Middel

Figure 37. Unaltered risk matrix of the muncipality of Dordrecht with in Dutch the description of organizational values, the COF and POF.