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Towards a better understanding of failures occurring in SUDS

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Towards a better understanding of failures occurring in sustainable urban drainage systems

Master Thesis Project

by

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Summary

In recent decades, sustainable urban drainage systems (SUDS) are more often seen as an addition to, or a replacement of, traditional piped urban drainage (UD) systems. SUDS promote onsite collection and conveyance of stormwater by stimulating and simulating natural hydrological processes. Unfortunately, failures in SUDS still occur regularly, resulting in malfunctioning systems, water nuisance and high costs. To learn from past experiences and to ensure that SUDS in the future can function as a credible alternative to piped UD systems, these failures should be identified and the underlying reasons more thoroughly understood. Therefore the research objective of this study is: *"Creating a better understanding of technical failures in SUDS and identifying their root causes."*

In order to create this understanding, this study empirically collected data on technical failures in SUDS by conducting site visits in 13 municipalities in the Netherlands. In addition, interviews were held with experts from the corresponding municipalities to gather information about the underlying root causes of the technical failures in these SUDS. Different analyses were carried out to process this data.

The 70 collected cases of technical failures in SUDS were categorized by different label categories to compare the failures. The categorization of the data revealed that SUDS with the same functionality (i.e. conveyance, infiltration, storage) encounter the same types of technical failures. Moreover, the data showed that interfaces between SUDS and subsystems are prominent failure locations. Furthermore, the categorization showed that most technical failures of this data set originated from the design phase. The interviews with experts resulted in the identification of 13 different root causes underlying the technical failures in SUDS. The observations showed that the implementation of SUDS in the urban environment present new interfaces between systems, disciplines and responsibilities. The interviews revealed that designers, constructors and operators often lack knowledge about these interactions and their impact on the performance of SUDS. Additionally, the interviews showed that *Poor communication between actors*, *Embedded practices of the urban sector*, and a *Lack of experience in the construction of SUDS* are often identified as root causes behind technical failures in SUDS.

Combining the results of technical failures and the underlying root causes showed that throughout the whole development process of SUDS (i.e. design phase, construction phase and user/maintenance phase) technical failures could arise. In minimizing these technical failures, every project phase should focus on certain root causes. This study showed that in the design process the focus should be placed on better understanding internal technical processes and the impact of subsoil characteristics on the performance of SUDS. In the construction phase, the focus should be more on educating constructors about SUDS in order to minimize construction failures.

By classifying the root causes this study revealed that root causes stem from uncertainties in technical, social and institutional systems and are located both within (internal) and between systems (interface). In comparing this to previous research, the classification showed that we should not only focus on the socio-institutional system but just as much on the technical system. Moreover, the classification showed that the interfaces between SUDS and other urban subsystems deserve extra attention in future projects.

This study empirically collected cases of technical failures in SUDS and provided insights in the underlying root causes of the failures. This may contribute in preventing future projects from making the same mistakes and therefore may contribute to better functioning SUDS. For future research it is recommended to systematically keep record of the problems and failures occurring in SUDS. This would provide credible insights to designers, constructors and operators in learning from past experiences.


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Acknowledgements

After writing this thesis, one thing has become certain: Walking in the rain will never be the same. When I was in Rome this summer and it started raining, I immediately scanned the area to observe how the stormwater drainage was arranged and where the stormwater could flow to. I obviously thought of myself as being quite a nerd at that time, but hey, it makes walking in the rain a bit more fun.

After six years of studying in Delft, this thesis is the final step to complete the master program Water Management (section Sanity Engineering) at Delft University of Technology. During the seven months of making my thesis, I was given the opportunity to visit many Dutch municipalities and to learn from experts in the urban water sector. Their input, their genuine involvement and our open conversations have helped me enormously and have made my thesis to what it is today. Therefore, I would like to thank all experts, since without their help, this thesis would not have been possible. Additionally, I owe many thanks to everyone who helped, supported and guided me. First of all, I would like to show my appreciations to my supervisors. Eva, for always being there to assist me, for her full devotion and incredibly detailed feedback, and for the coffees and homemade cakes that made every meeting something to look forward to. Jeroen, for trusting in me and giving me the freedom to explore this thesis project in my own way. Frans, for sharing his valuable connections in the water sector with me and for providing clear and concise feedback in the limited time he has. To my friends, Swaen, Juliette, Tycho, Markus, Joris and Jeroen for their ever-present friendship throughout our master. And last but not least to my family, for their unconditional love and support.

During my bachelor Civil Engineering I learned to approach problems from a technical point of view. This thesis challenged me to connect this technical perspective with social and institutional perspectives. Combining technology, people and processes in this master thesis has helped me to become a real Civil engineer.

Vita Vollaers
Delft, October 2019

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Chapter 1

Introduction

Last decades, the growing political focus on pollution control and environmental protection have caused concerns about the effective usage of traditional piped urban drainage (UD) systems (Chocat et al., 2007). In response to these environmental concerns, a trend from using conventional piped UD systems towards more sustainable UD systems has been visible (Qiao et al., 2018). New techniques of more sustainable UD systems have been extensively researched and implemented across the globe (Fletcher et al., 2015). Sustainable Urban Drainage Systems (SUDS) have been developed in Europe and promote onsite collection and conveyance of stormwater by simulating natural hydrological processes, thereby contributing in environmental, social and economic sense to the urban environment (Bozovic et al., 2017). Although the added value of SUDS is widely recognised in the urban water sector, successfully integrating them in the urban environment remains a challenging and complex task (Zhou, 2014).

The function of SUDS can range from only a stormwater management function to a combination of a hydrological, ecological and built environment functions (Hoang and Fenner, 2016). Because of this multifunctionality, SUDS present new interfaces with other subsystems in the urban environment, both below- and above ground (e.g. roads, greenery, houses). The new interfaces between subsystems introduce new interactions between actors from multiple disciplines (Hoang and Fenner, 2016). Implementations of SUDS in practice often underestimate the complexity of these new interactions, causing the performance of SUDS often not meeting its requirements (Zhou, 2014).

The implementation of SUDS in the urban environment requires changes in the traditional design of the public and private space in order to make conveyance, infiltration and storage of stormwater possible. Therefore SUDS intervene with many traditional considerations, making carefully allocating new systems in spatial planning important (Zhang and Chui, 2018).

Tradition UD systems are founded by many years of practice, creating well ingrained guidelines and expertise of actors involved. Since SUDS are relatively new technical developments, there still exists limited understanding of the new responsibilities and management requirements and limited knowledge about the long term performance (Brown and Farrelly, 2009).

1.1 Problem statement

In recent decades, SUDS have been implemented as an addition to, or as a replacement of, piped urban drainage system. In practice, SUDS do not always perform to an adequate standard due to technical failures. To ensure that future implementations of SUDS meet the set requirements and ultimately function as credible alternative to piped UD systems, a better understanding of the reasons behind failures in SUDS is needed.

Previous studies focused on the performance of SUDS in their own context (Scholz and Grabowiecki, 2007), (Geiger et al., 2009) and (Xie et al., 2019). However, it is known that SUDS introduce new interfaces with other urban systems in the urban environment, both below- and above-ground (Hoang and Fenner, 2016). The impact of these interactions on the performance of SUDS is yet underexposed.

In addition, many studies have focused on the impediments in the transition of the conventional towards more sustainable urban drainage systems (Brown and Farrelly, 2009), (Qiao et al., 2018). These impediments gave insights in the institutional barriers which underlie the slow implementation of SUDS. However, these studies concluded that the reasons for this slow implementation lie predominantly within the socio-institutional system. It is almost forgotten that many SUDS have been implemented in the past 20 years, but technically do not always perform to an adequate standard. Focusing on a faster implementation seems therefore premature, as this will not solve the technical problems that SUDS currently face.

There exists a research gap in the understanding of technical failures in SUDS and their root causes. This thesis aims to contribute to previous research by creating a better understand in the root causes of failures arising in SUDS.

1.2 Research aim

To ensure that SUDS in the future can function as credible alternative to piped UD systems, the objective of this thesis is to create a better understanding of technical failures in SUDS and their underlying root causes. In order to create this understanding, data about technical failures of implemented SUDS in the Netherlands is collected, interviews with experts are held and in-depth research is carried out.

1.3 Research questions

The following five research questions have been formulated in order to meet this objective:

1. How are new urban drainage systems being defined?
2. What failures in SUDS have already been reported?
3. How can technical failures in SUDS be categorized?
4. What are the root causes behind technical failures occurring in SUDS?
5. How can the root causes help future projects in preventing technical failures of SUDS?

1.4 Scope

This study will focus on the technical failures regarding the water management function of SUDS for stormwater management of Dutch urban areas. The scope of this research is demarcated by the following aspects:

1. This research will use the term Sustainable Urban Drainage System (SUDS) that is already used for 20 years in Europe, to define all urban drainage systems next to, or instead of, the conventional piped urban drainage system. This consists not only of 'blue' or 'green' urban drainage systems, but also 'red' (roof) and 'black' (streets) drainage solutions.

2. For this research a 'technical failure' is defined as a situation where the used system cannot perform its function properly. This study focuses on the failures in terms of the water management function of SUDS. This includes failures with respect to the hydrological performance, the quality of the water, the impact of water on the ecology and performance of recreational activities.

3. This study looks at all SUDS located in the area starting from the roof to the surface water body.

4. This research is carried out in The Netherlands and therefore only looks at Dutch SUDS.

1.5 Research design

In Chapter 2, a literature study is carried out to gain insights into new UD systems, the challenges that SUDS face and effective ways to categorize SUDS. A visualisation of the research design is presented in figure 1.1.

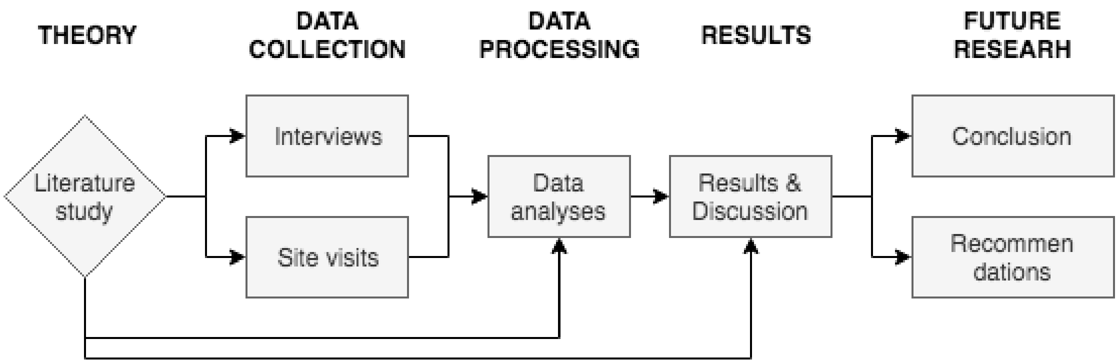

Figure 1.1: *Visualisation of the research design*

The data on technical failures in SUDS is collected by qualitative interviews with experts and multiple site visits to urban areas in the Netherlands where SUDS are implemented. Two sources of data are collected: Interview data and system observation data. Chapter 3 elaborates on this data collection process.

The collected data is processed by three analyses, the categorization analysis, the root cause analysis and the synthesis in Chapter 3. The system observation data is categorized by certain label categories, partly derived from literature and partly from the empirical research. The interview data is used to identify root causes underlying the technical failures. The synthesis combines the results from the categorization and the root cause analysis.

In Chapter 4, the results obtained from the analyses are presented and discussed. The conclusions and recommendation arising from the results are presented in Chapter 5 and 6.

Chapter 2

Literature Study

This chapter focuses on finding the answers to the following questions:

1. How are new urban drainage systems being defined?
2. Which challenges and failures regarding to SUDS have been reported?
3. How can technical failures in SUDS be categorized?

2.1 Urban stormwater management

Stormwater management is the collective name for the collection and transport of stormwater in urban areas. The conventional approach to stormwater management is based on the construction of underground piped infrastructure with the main goal of collecting and conveying stormwater away from urban areas (Zhang et al., 2017). In general, there are two types of sewer systems, combined sewer systems and separated sewer systems. In combined sewer systems, storm- and wastewater are being collected in one pipe. Separated sewer systems separate storm- and wastewater in two pipes. For both sewer systems, the impervious surface of urban areas is connected to the underground drainage system which collects the stormwater runoff. The separated stormwater drainage system is designed to convey this runoff directly towards receiving water bodies, with limited or no treatment (Burns et al., 2012).

The conventional sewer system in The Netherlands is dimensioned to transport a rainfall event with a return period of 2 years (T = 2 years) (Rioned, 2016). In the past 60 years, weather characteristics have changed due to climate change. Therefore the return periods do not seem to be representative for the the current precipitation events any longer (KNMI, 2011).

2.1.1 Challenges: Environmental pollution

The Water Framework Directive (WFD) agreed in 2000 on standards for the water quality of regional water bodies. These standards were generally not reached in 2015 in the Netherlands (Stowa, 2017). There are many factors that impact the water quality in the Netherlands, including insufficient treated discharges and sewage overflows, emissions from industry and traffic (OECD, 2014). Dutch municipalities are working hard to find strategies to improve water quality.

In dutch urban areas two main types of urban drainage systems are being used, combined- and separated sewer systems. Since the early 1970s, separated sewer systems have been introduced in Dutch urban areas to counteract the disadvantages of the combined sewer systems (e.g. sewer overflows) and to optimize the performance of waste water treatment plants. It has become evident that separated sewer system also have drawbacks (Hoes et al., 2009). Illicit connections where stormwater or waste water ends up in the wrong pipe, occur regularly and result in the pollution of receiving waters.

Moreover, urban stormwater runoff can contain a variety of contaminants, collected when the stormwater flows over impervious surfaces (Huang et al., 2016). For separated sewer systems, the stormwater is transported directly to the surface water without further treatment. This can also decrease the water quality of regional water bodies.

To improve the quality of urban stormwater and to reduce peak flows, Dutch municipalities aim for strategies to retain, store and drain stormwater (Tielrooij et al., 2000). Above-ground drainage and infiltration of stormwater can form a solution to minimize illicit connections and improve the quality of the stormwater. To stimulate water quality improvement and sustainable urban water management, national policies and regulations are present in the Netherlands that encounter this (referring to Appendix A for more information).

2.1.2 Challenges: Urbanisation & climate change

In recent decades urban stormwater systems have been challenged by the adverse effects of climate change, urbanisation and intensification of urban land use (Fletcher et al., 2015).

The population of Dutch urban areas is growing. The PBL (planning office for living environment) predicts that urbanisation will further increase in the coming decennials (Nabielek et al., 2016). This expansion has resulted into changes in the urban land cover by increased impervious surface areas (i.o. roofs, roads and bike paths) (Burns et al., 2012). Accordingly, these changes affect the hydrological response of urban catchments and flood risk has increased (Skougaard-Kaspersen et al., 2017). Urban areas are characterized by their high peak flow volumes and fast runoff rates, namely due to the high percentage of imperviousness. Urbanisation ensures a further increase in these factors (Zhou, 2014).

Climate change will induce an increase in the severity and intensity of rainfall events, temperature rise and an increase of dry periods (IPCC, 2015). An increase in rainfall events and more extreme rainfall events enlarges the pressure on the urban water system. As the capacity of the urban water system is not designed for extremities, more pluvial flooding of urban areas in The Netherlands will be induced (STOWA, 2016).

SUDS were already introduced in urban areas before the effects of climate change and urbanisation became evident. However, SUDS turned out the be very functional to mitigate the adverse impacts of climate change and urban development Skougaard-Kaspersen et al. (2017).

2.1.3 Response to challenges: Sustainable stormwater management

The need to improve the quality of stormwater before it enters the surface water and the need for peak flow reduction have led to new stormwater management strategies (Burns et al., 2012).

The development towards new stormwater management strategies has received growing interest and attention all across the world, enabling the parallel development of new terminology aiming to describe new approaches (see figure 2.1) (Goulden et al., 2018). The development led to terminology of systems dealing with stormwater in similar way. The term Low-Impact Development (LID) is used New Zealand and North America and describes an approach that focuses on minimizing the cost of stormwater management. In Australia the term Water-Sensitive Urban Design (WSUD) has been introduced. This approach includes sustainable stormwater management as key part to design a water-sensitive urban area. The term Sustainable Urban Drainage Systems (SUDS), originating from the UK, stands for specific techniques and systems that aim to drain stormwater in a more sustainable way than conventional drainage systems. In The United States and Canada the term Best Management Practices (BMPs) serves as approach to prevent pollution (Fletcher et al., 2015).

Additionally, terms that aim for sustainable development in a more broader principle have emerged, see Figure 2.1. The broader principles aim to: 1) mimic natural processes and mitigate changes to hydrology, 2) improve the water quality and reduce pollutants (Fletcher et al., 2015). For example, the term Green Infrastructure (GI) represents infrastructure that incorporates natural landscapes in the public space and Blue-Green Infrastructure (BGI) represents infrastructure that combines both water management and natural landscapes in the public space. BGI can be used for stormwater management as measures providing storage and retention solutions for rainfall runoff problems by nature based ecosystem services (ES). Thereby they contribute in environmental, social and economic sense to the urban environment. The uptake of BGI in stormwater management, results in Sustainable Drainage Systems (SUDS) or Best Management Practices (Thorne et al., 2018).

The collective name 'blue-green measures' stands for all BGI that apply ecosystem services to deliver climate adaptation benefits to urban areas (Voskamp and de Ven, 2015)(Ashley et al., 2018). For climate adaptation practices, the implementation of multiple ecosystem services, combining their strengths and functions creates synergy and serves as best solution (Voskamp and de Ven, 2015). Blue-green measures enhance climate adaptation by increasing the resilience of urban areas against the adverse effect of climate change (Bozovic et al., 2017).

Additionally, there are exist strategies aiming for sustainable management of stormwater on a larger scale. The term Sponge City (SPC) is initiated in China in 2014 and serves as a nation-wide strategy to deal with urban pluvial flooding while stimulation ecosystems and the environment. This is done by the implementation of blue-green infrastructure in the form of SUDS (Li et al., 2016).

It can be concluded that over the years many terms have emerged that represent specific systems, concepts or broad principles aiming for sustainable urban water management. This study aims to incorporate all systems that deal with stormwater in another way than the conventional piped urban drainage system. From figure 2.1, it can be seen that only three terms match with specific techniques for urban stormwater management, namely

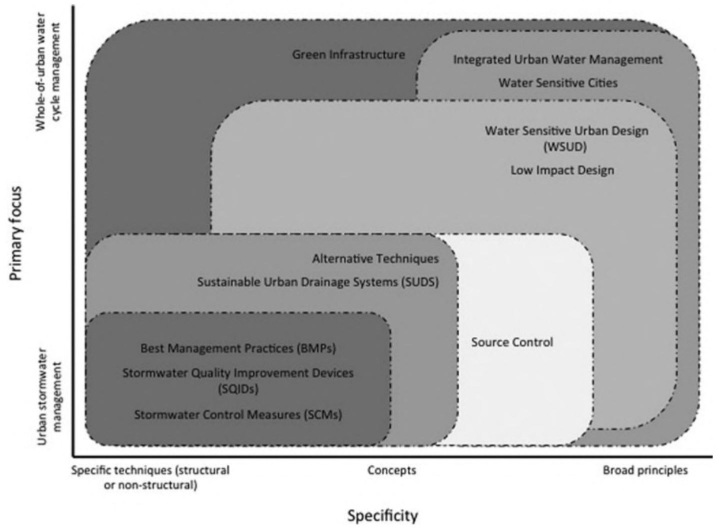

Figure 2.1: *The classification made by Fletcher et al. (2015) of urban drainage systems terminology, based on the specificity and primary focus*

BMPs, SQIDs and SUDS. From these terms, SUDS matches these requirements best: SUDS specifically represent structural urban drainage systems, whereas BMPs orginates from a non-structural perspective; the term SUDS is used in Europe, whereas SQIDs is only used in Australia and BMPs predominantly in the USA. For these reasons, the term sustainable urban drainage systems (SUDS) is used in this report.

2.1.4 Response to challenges: Transition towards more sustainable stormwater management

Many researchers have focused on the identification of barriers, impediments or challenges in the transition from conventional towards SSM practices. They can be referred to as 'barriers for implementation' (Brown and Farrelly, 2009). This study aims to find the root causes behind technical failures in SUDS, that is fundamentally different than barriers for implementation. However, the identification of barriers can help gaining insights in the weaknesses in socio-institutional structures that may allow root causes of technical failures to arise.

The research of Roy et al. (2008) particularly focuses on impediments to watershed-scale implementation of SSM. In this research they focus on seven major impediments that must be bridged in order for WSUD to be achieved, see Appendix B.1. It is noted that only one of the impediments to WSUD is technical: *'Insufficient engineering standards and guidelines.'*. Roy et al. (2008) indicated that in some cases, traditional standards and guidelines prevent project developers from implementing WSUD systems in urban areas. When permeable pavements could be used at a certain location but lack sufficient performance standards, standardized procedures often still require the implementation of curbs and gutter systems alongside to new developments. This does not encourage project developers to implement WSUDs (Roy et al., 2008).

Brown and Farrelly (2009) conducted an extensive literature review and identified 12 institutional barrier types that impede widespread SUWM implementation. The 12 barrier types were subjected to a institutional capacity assessment framework (figure

2.2 in order to detect capacity shortages. From this the conclusion was drawn that the barrier types are rather socio-institutional than technical and they relate mainly to inter-organisational capacity shortages and external rules and incentives. Moreover, they explained that barriers are highly interdependent and cyclic. Meaning that the presence of a certain barrier results into other barriers (Brown and Farrelly, 2009).

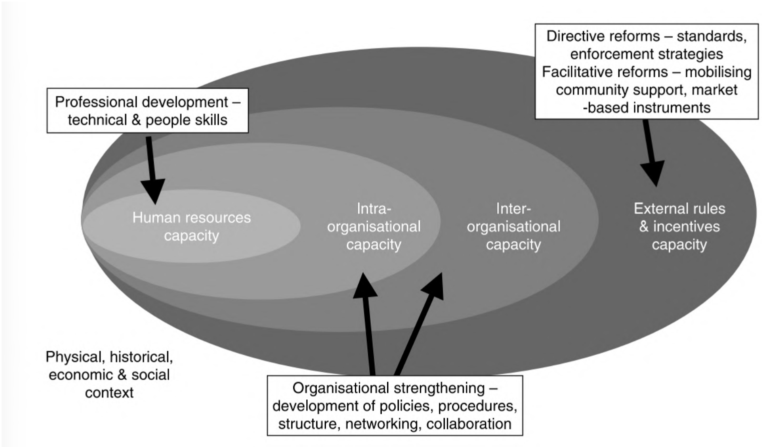

Figure 2.2: *Institutional capacity assessment framework*

The transition from conventional stormwater management towards SSM is often limited by the slow implementation of its infrastructure. The literature study from Qiao et al. (2018) examined and summarized the governance factors impacting the slow implementation of the GI infrastructure (presented in Table B.3 in Appendix B). The research of (Roy et al., 2008) and (Brown and Farrelly, 2009) are taken into account in this research. They concluded on three critical factors (Qiao et al., 2018): 1) General lack of knowledge related to SSM, resulting in a lack standards and guidelines incorporated in legislation. Therefore unclear distribution of responsibilities exists, 2) Lack of funding and space, 3) Lack of communication between actors because of mutual mistrusts.

Marlow et al. (2013) conducted a critical reassessment and approached the transition towards sustainable urban water management (SUWM) from a different perspective. They provided alternative insights into why SUWM implementation remains slow, and referred to four 'conceptual weaknesses' that are associated with the arguments for SUWM: 1) difficulties in predicting the system effects of innovative solutions, 2) practical challenges in managing innovations in technologies and service provision strategies, 3) financial considerations and 4) the effect of bias and advocacy on the promotion (Marlow et al., 2013). When supporting specific technical systems for SUWM from a 'willingness for change' perspective, the risk arises that the advantages and disadvantages of certain system are not fairly assessed towards SUWM (Marlow et al., 2013).

In conclusion, the 'barriers for implementation', 'impediments' and 'conceptual weaknesses' identified in the transition from conventional towards more sustainable stormwater management cannot be directly translated to root causes behind technical failures in SUDS systems. However, they do provide insights in the difficult processes occurring in socio-institutional structures.

2.1.5 Uncertainty and complex socio-technical systems

When designing new infrastructure, the greatest challenge is to correctly deal with all the uncertainties that will arise during the life span of the system (Herder et al., 2008). The research of Nieuwenhuis (2018), aimed to better understand the role of uncertainties in decision-making of integrated urban drainage systems. To classify the uncertainties that experts have experienced in the lifetime of integrated urban drainage systems, she composed a framework based on the two dimensions: the location of uncertainties (i.e. within the urban drainage system or between systems) and the nature of the uncertainty (i.e. technical, social, institutional), see Table 2.1.

Table 2.1: *The uncertainty framework (Nieuwenhuis, 2018)*

	Internal uncertainties (within the system)	**Interface uncertainties (between systems)**	**External uncertainties (outside the system)**
Technical uncertainties	Uncertainty about the technical functioning of the focal system	Uncertainty about technical interactions between the focal and other systems	Uncertainty in the environment
Social uncertainties	Uncertainty about the actors decision for the focal system	Uncertainty about actors decision for related systems	
Institutional uncertainties	Uncertainty about institutions for the focal system	Uncertainty about institutions for each related system	

The literature study carried out by Nieuwenhuis (2018) described that urban drainage systems are complex socio-technical system, located in a large-scale urban environment with many other subsystems. These subsystems (e.g. roads, buildings, pipes, surface water) are all interdependent in various ways (Herder et al., 2008). Moreover, these subsystems behave differently, involve different actors and can therefore have conflicting relationships. The relationships and interdependences result in high system complexity, which makes the interaction between subsystems and the interaction between the actors involved hard to understand and predict (de Bruijn and Herder, 2009).

When changing the technical part of a complex socio-technical system the outcome is very hard to predict and it is often unknown how the performance is impacted (Weijnen and Bouwmans, 2006). System innovations bring additional complexity.

2.2 Sustainable Urban Drainage Systems (SUDS)

The term SUDS is used to describe systems that drain stormwater in more 'sustainable' way than conventional urban drainage systems. This can be achieved by mimicking natural drainage processes (e.g. pre-development runoff, infiltration, evopotranspiration)(Fletcher et al., 2015). SUDS can be placed in a continuous cycle to join forces, forming a 'management train'. In this management train, SUDS are submerged in four types of approaches to manage stormwater (Fleming et al., 2005): prevention, source control, site control and regional control.

Traditionally, SUDS are developed to improve the quality of stormwater and receiving water bodies and reduce peak flows. However, SUDS nowadays also effectively drain design storms. They thereby function as credible alternative to the conventional piped drainage systems (Fletcher et al., 2015). Duffy et al. (2008) concluded that if SUDS are well designed, they are less expensive to construct and maintain than conventional urban drainage systems. Therefore, SUDS are seen as a cost-effective alternative to conventional drainage systems.

2.2.1 Multifunctionality

CIRIA (2015) described that SUDS have the ability to achieve multiple benefits in one design (Figure 2.3): water quantity, water quality, amenity and biodiversity. The concurrent existence of various benefits lead to a multifunctional system. This is one of the core advantages of SUDS.

Lähde et al. (2019) used these four criteria of SUDS to measure multifunctionality. The conclusion was made that the criteria show mutual interdependencies. When multifunctionality is desired in a complex urban environment, the design process must take the interdependencies between the criteria into account and must also include other urban functions. Moreover, (Fratini et al., 2012) states that in order to develop multifunctional solutions, interactions between different disciplines must be created, creating transdisciplinary actions.

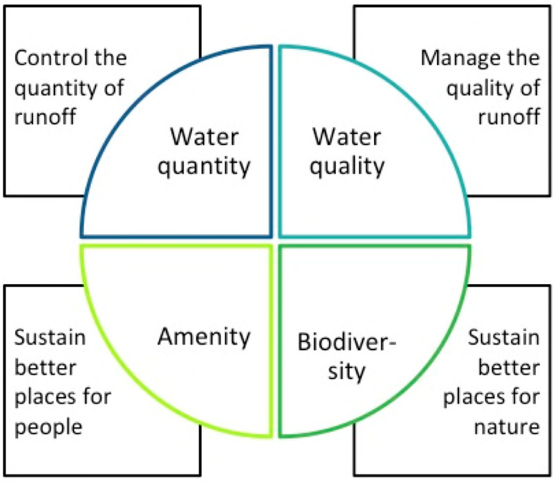

Figure 2.3: *Multifunctionality of SUDS described by the coexistence of four pillars (CIRIA, 2015)*

2.2.2 Challenges

Due to the multifunctionality of SUDS, their function can range from only a stormwater management function to a combination of a hydrological, ecological and built environment function (Hoang and Fenner, 2016). Because of this multifunctionality, many disciplines are involved in the decision making process. In this process all disciplines have the tendency to mainly strive for their own objectives (Zhou, 2014). This can result in a design that does not satisfy all disciplines.

Moreover, the multifunctionality leads to new interactions of SUDS and other urban subsystems. Hoang and Fenner (2016) investigated these system interactions of SUDS within the urban environment in order to gain insights in the interdependencies between urban subsystems. They conclude that new system interdependencies between SUDS and other urban subsystems represent new complexities (Hoang and Fenner, 2016). For example, they stated that optimizing the performance of SUDS requires the involvement of multiple sectors. This involvement will lead to new complexities concerning compromising on objectives and collaborate on decisions.

To maximize the multifunctional benefits of SUDS, spatial allocation in the urban environment is critical (Zhang and Chui, 2018). The availability of space for new innovations remains a big challenge. SUDS intervene in the urban areas with traditional technical, social and institutional considerations because of the complex interactions between environment, actors and infrastructure. Therefore, SUDS must be carefully allocated in the urban area to prevent unwanted interactions (Zhang and Chui, 2018).

According to Zhou (2014), the complexity of SUDS is underestimated by actors involved, which causes poorly considered actions and eventually insufficiently performing SUDS. Other reasons that cause insufficient SUDS performance are: 1) lack of experience with the operation and maintenance of SUDS; 2) misunderstanding of the interaction of SUDS with other water systems Zhou (2014). In the case study research by Heal et al. (2009) the conclusion is drawn that more education about SUDS is needed. Poorly considered actions made by designers, constructors and maintenance staff can have a disadvantageous impact on the performance and the costs of maintenance of SUDS.

To conclude, the implementation of multifunctional SUDS lead to the involvement of more actors from multiple disciplines and creates new interdependencies between urban subsystems which did not exist within conventional urban drainage systems. The involvement of more actors and new interactions increase the complexity and makes it very hard to predict the performance of these new systems.

2.2.3 Categorization of SUDS concepts

This study aims to collect practical cases of technical failures in SUDS. However, all SUDS have different characteristics and context, making it difficult to compare the cases.

The Amsterdam Rainproof organisation uses two types of 'label categories' to categorize the rainproof measurements that contribute to a rainproof urban area (Rainproof, 2019a). The first label category is 'Solution type' with labels: *water retention, water drainage, infiltrate water, use water and building water-robust.* The second label category is 'Location' with labels: *roof, garden, street, square, park, neighborhood.* Furthermore, the atelier GROENBLAUW introduced the webpage 'Urban Green-Blue grids', presenting the online version of the book from Pötz and Bleuzé (2012). They also subdivide water solutions into different categories.

The research of Fleming et al. (2005) has categorized SUDS in six different types systems: conveyance systems, infiltration systems, filtration systems, retention systems, detention systems and constructed wetlands. There is some overlap between the systems. This study makes a distinction between three types of SUDS: infiltration systems, conveyance systems and storage systems. This research elaborates on the advantages and disadvantages of different systems in the subsequent sections.

2.2.4 Conveyance systems

Conveyance systems aim to collect and transport stormwater in another way than the traditional piped system. The above-ground drainage of stormwater is elaborated on in the subsequent section.

Above-ground drainage

Above-ground drainage systems transport the stormwater from roofs and streets over the surface towards an infiltration or storage facility. Above-ground drainage can be achieved by using open gutters (from various materials), covered gutters and open water channels (Pötz and Bleuzé, 2012). By transporting stormwater above-ground, less piped stormwater sewers have to be constructed. This saves costs and minimizes the chance of illicit connection. An additional advantage is that above-ground drainage makes stormwater visible, making residents more aware of stormwater drainage. As a result, residents will less likely dispose inappropriate substances or waste on the street (Pötz and Bleuzé, 2012).

Figure 2.4: *Above-ground drainage from a private plot to the street*

Figure 2.5: *Above-ground drainage from the house almost directly on the street*

There are some disadvantages about the above-ground drainage of stormwater. In some cases, houses are directly connected to the sidewalk, without a front yard. In the winter snow falls on the roof of the house. When the snow melts, it is transported via the gutters towards the street, where it turns into ice again due to the temperature of the pavement that is still below zero degrees. This results in a slippery sidewalk and can lead to dangerous situations (Boogaard et al., 2006). Additionally, algae growth can cause slippery roads in north-facing streets (Boogaard et al., 2006). Furthermore, open gutters in gardens must be constructed in order to transport the water to the plot boundary. These gutters can form a barrier in the design of the garden or residents can experience that as such (Boogaard et al., 2006). In addition, there must be sufficient slope in the garden or street to be able to drain the water properly. Otherwise, stormwater flows to unwanted place or stagnates and forms puddles, causing water nuisance (Pötz and Bleuzé, 2012). Finally, when designing above-ground drainage, it is important to take into account the location of speed bumps and driveways in such a way so that they cannot block the water (Rainproof, 2019b).

This shows that common risks and failures of above-ground drainage are; the ice formation on the street causing poor walkability on the street, an insufficient slope of streets for water transport, complications for the garden design, the interference of traffic obstacles; moisture spots on houses or buildings.

2.2.5 Infiltration and storage systems

An infiltration system is a system that enables the stormwater to infiltrate into the subsoil layer. RIONED (2006) makes a distinction between three types of infiltration systems: subsurface infiltration, surface infiltration or permeable paving. Infiltration systems are in many cases combined with storage capacity, both above- and below ground. Therefore, these two are combined in this section.

- **Subsurface infiltration facilities** are often constructed from elements (i.o crates) or are simply realized as a soil improvement (i.o coarse sand and granulate).
- **Surface infiltration facilities** are often designed as a ground level reduction in the form of a ditch. These facilities have a large storage space and transport capacity. More storage means less required infiltration capacity.
- **Permeable pavements** are part of the draining surface. The trench under the pavement stores the rainwater. The storage facility is often dimensioned relatively large to prevent overloading.

Subsurface infiltration & storage: Crates

Infiltration crates are underground filtration facilities that are able to temporarily store and slowly infiltrate stormwater to the groundwater. Infiltration crates are plastic crates that are covered with geotextiles to prevent them from silting up. Crates form a good solution when there is no capacity to store water above the ground (Rainproof, 2019a). Crates can be constructed in all different shapes and sizes.

Figure 2.6: *Construction of infiltration crates at the Emmastraat in Gouda*

Figure 2.7: *Realization of crates constructed under the Emmastraat in Gouda*

Due to a lack of maintenance, a prominent failure of infiltration crates is clogging. Boogaard and Wentink (2007) investigated the clogging mechanisms of infiltration crates. By conducting interviews and surveys in several Dutch municipalities, they came to the conclusion that municipalities are not aware of the clogging problem and the need for maintenance of infiltration crates.

Boogaard and Rombout (2008) aimed to capture the long-term environmental performance of subsurface infiltration facilities. Boogaard and Rombout (2008) explained that the risks associated with subsurface infiltration facilities are different from those of above-ground facilities, due to the difference in location and conditions. For subsurface infiltration facilities, for example, there is a greater risk of illicit connections because of limited visual inspection. From site visits they noted that many subsurface infiltration facilities could not be properly inspected and were difficult to clean. They therefore recommend to take the maintainability of systems into account in the design.

Surface infiltration and storage: Swales

Swales both function as infiltration- and storage systems designed for flow control and water quality improvement. The peak load towards the sewer is therefore reduced. Bioswales consists of a vegetation layer, a coarse porous layer and a drainpipe (Pötz and Bleuzé, 2012). Each bioswale has an overflow system, were excess water can flow towards the stormwater sewer.

Figure 2.8: *Bioswale implemented in Utrecht*

Figure 2.9: *Bioswale implemented in Dordrecht*

As stormwater flows above-ground, this water can contain heavy metals originating from roofs, roads and cars. When the water infiltrates in the soil, percentages of these heavy metals may remain in the soil of the bioswale. The degree of contamination of heavy metals (Copper, Zinc and Lead) in the subsoil of the bioswales were investigated in a recent study by RIONED, Stowa and the Hanzehogeschool (2019). The conclusion was that 20% of the locations tested (were the bioswale was already present for 10 years) contained higher concentrations of heavy metals than the reference level. Furthermore they show a spatial distribution of the contamination. At the inflow points the concentration was higher than in the middle of the bioswale.

The publication of Boogaard et al. (2006) examined the experiences with bioswales in The Netherlands. The maintenance of the swales entails a number of specific points of attention, namely: the formation of tracks and the compacting of the soil during machine mowing, the formation of spots without vegetation, leaf accumulation on the grass surface. As a result, the maintenance deviates from a regular turf. From an organizational point of view, the maintenance of swales requires more coordination between different departments within the municipality than with a 'normal' turf.

Porous and permeable pavements

The main capacity of porous and permeable pavements is reducing stormwater runoff to drainage systems by absorbing stormwater into the subsoil. Porous and permeable pavements have no capacity to buffer or store rainwater (Pötz and Bleuzé, 2012). There is a clear difference between the two, permeable pavement systems make infiltration of stormwater possible via the open joints between the bricks, porous pavement system make infiltration possible through the permeable bricks. In recent years, permeable pavements have become widely used SUDS in urban areas (Huang et al., 2016).

Scholz and Grabowiecki (2007) summarized the literature mainly on permeable pavement systems and described a clear difference between porous and permeable pavement. Where permeable pavement systems are identified as successful and important SUDS

Figure 2.10: *Permeable pavement implemented on a square in Amsterdam*

Figure 2.11: *Permeable pavement constructed at parking places in Zwolle*

in literature, porous pavements are more seen as problematic due to clogging problems. Geiger et al. (2009) concluded that permeable- and porous paving systems should not be used extensively for car parking lots and roads due to the pollution risk and inability to bear heavy loads. Xie et al. (2019) have also indicated clogging and heavy load impacts as bottlenecks, together with damage from freezing.

This shows that most common failures and risks of infiltration and storage systems are; clogging, the risk of pollution, the formation of tracks during machine mowing, the compaction of the soil during machine mowing, the formation of spots without vegetation, the accumulation of leafs on the grass surface, heavy loading.

2.3 Conclusions from the literature study

The conclusions from the literature study are presented below:

Research question 1: How are new systems aiming for sustainable stormwater management defined?
Over the years many terms have emerged that represent specific systems, concepts or broad principles aiming for sustainable urban water management (e.g. LID, BMP, WSUD, SUDS). This study aims to incorporate all systems that deal with stormwater in another way than the conventional piped urban drainage system. The term Sustainable Urban Drainage System (SUDS) matches these requirements best and will be used in this report.

Research question 2: Which challenges and failures of SUDS are already reported?
The literature review revealed the implementation of multifunctional leads to the involvement of more actors from multiple disciplines and creates new interdependencies between urban subsystems which did not exist within conventional urban drainage systems. Moreover, the the spatial allocation of SUDS in the urban environment is critical, due to traditional considerations in the urban environment. This increases the complexity and makes it very hard to predict the performance of these new systems.

This literature study showed that the most common risks and failures of infiltration and storage systems are identified as: clogging, maintainability of the SUDS, pollution risk, insufficient water retention capacity and unsuitability of subsoil. The most common failures for conveyance systems are reported as: the ice formation on the street causing poor walkability on the street, insufficient slope for transport, complicating garden design, interference of traffic obstacles and no proper drainage causing moisture spots on houses or buildings. These technical failures in SUDS are presented in figure 2.12. The main reasons identified that cause malfunctioning SUDS are: 1) underestimation of the complexity of SUDS by actors involved, 2) lack of experience with the operation and maintenance of SUDS 3) misunderstanding of the interaction of SUDS with other water systems 4) the lack of knowledge about SUDS by designers, constructors and maintenance staff.

Moreover, the literature study revealed that many researchers have focused on the identification of barriers, impediments or challenges in the transition from conventional towards more sustainable practices, referred to as 'barriers for implementation'. These barriers for implementation are according to different researchers namely socio-institutional rather than technical. Barrier could be translated to the understanding of root causes behind technical failures in SUDS, the main objective of this study. For example, *Insufficient engineering standards and guidelines.* is named by Roy et al. (2008) as impediment for the widespread implementation of WSUD. When SUDS are implemented, without sufficient engineering standards, it is not known whether the systems will function as required. This can impact the functionality of the system. Moreover, the conceptual weaknesses that Marlow et al. (2013) refers to could also be translated to root causes behind technical failures in SUDS. For example, *difficulties in predicting the system effects of innovative solutions* suggests that when an innovative system is implemented, the system effects cannot always be predicted. This can results in unforeseen system effects that could have a negative impact the functionality in SUDS.

How can technical failures in SUDS be categorized?
This literature study showed that different SUDS concepts can be clustered by making use of categories, presented in figure 2.12.

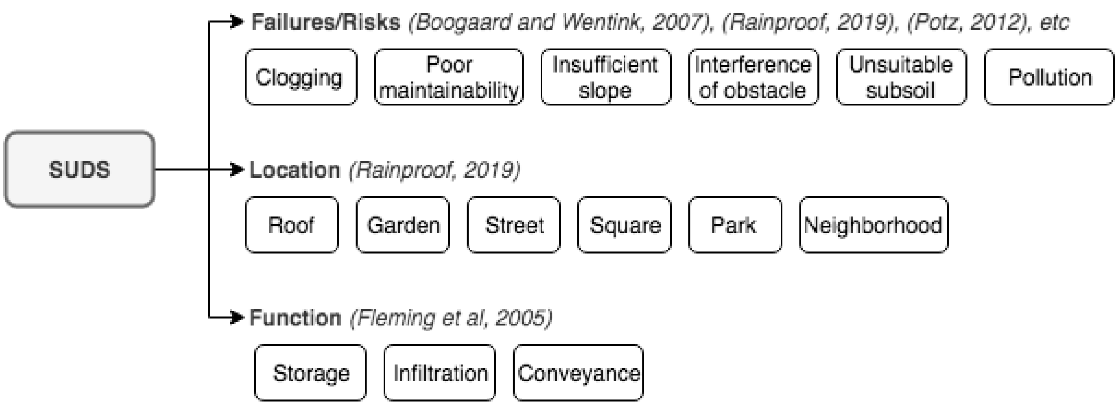

Figure 2.12: *Categorization of SUDS*

Chapter 3

Research methodology: data collection

This chapter elaborates on the research methodology that is used to collect data on technical failures in SUDS.

3.1 The cases

To collect empirical data on technical failures in SUDS, 13 urban areas throughout the Netherlands were visited. In each urban area a qualitative interview was held with an expert followed by site visits where pictures of SUDS were taken. For each site visit, the goal was to collect 'cases' of SUDS where technical failures occurred. Each visit to an urban areas consisted of four stages 1) preparation, 2) interview 3) site visit and 4) processing of data. The steps taken in each stage are further elaborated on in figure 3.1.

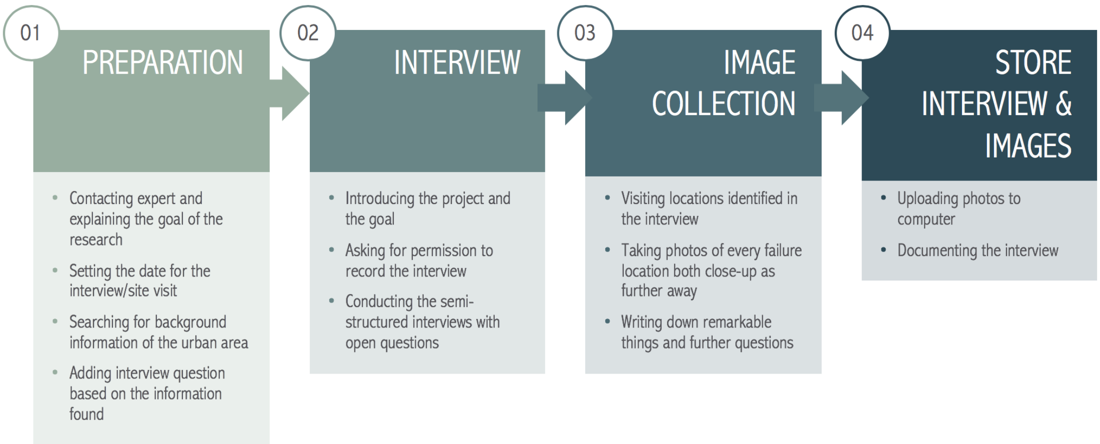

Figure 3.1: *The four steps that where followed for every study site; preparation, interview, image collection and storing the interviews and images*

3.1.1 Study sites & selection

The urban areas, hereafter referred to as 'study sites', were selected based on certain criteria. The four criteria were as follows:

- the presence of SUDS;

- the location of the urban area (providing a representative image of the Netherlands, both in terms of subsoil conditions as geographical spreading);
- the type of area (new/existing areas);
- the willingness of an urban water expert to participate in the research.

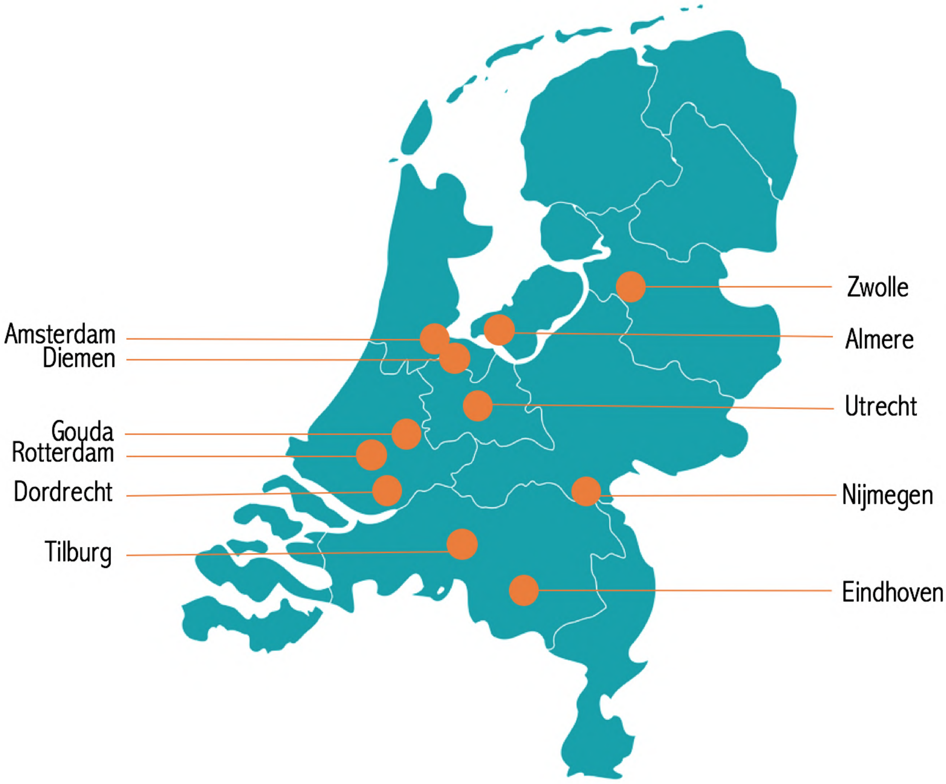

Figure 3.2: *The study sites of this research*

In order to select study sites a list of dutch urban areas was formulated together with a committee member based on prior information about locations where SUDS were applied. When this list was set up, the geographical spreading (see figure 3.2) and subsurface characteristics of these urban areas were taken into account in order to ensure that various area types were included in the data set. Urban water experts with knowledge about the water systems in that urban area were then added to the list. Eventually, 13 study sites were visited. In two municipalities (Nijmegen and Zwolle), data from two districts (newly developed areas and retrofitted areas) was collected. From the total amount of 13 study sites, five were located in newly developed areas and 8 in retrofitted areas. The newly developed areas are designed based on SUDS principles. In the retrofitted areas, individual systems were implemented, often next to the conventional piped system.

In table 3.1 the study sites representing newly developed areas are presented. Table 3.2 shows the retrofitted study sites.

3.1.2 Interview

After the preparation, interviews were conducted with experts who had knowledge about the performance of SUDS implemented in the corresponding study site. The interviews

Table 3.1: *The characteristics of study sites in newly developed areas. The table presents the size, landscape type, SUDS types and stormwater transport principle of the area.*

Study site	Area (km2)	Soil condition	SUDS types present	Transport principle
Eindhoven Meerhoven	15,4	Sand	Subsurface storage	Piped
Zwolle Stadshagen	15,2	Sand	Porous- & permeable pavement, crates	Piped
Nijmegen Waalsprong	13,5	Sand	Bioswales	Non piped
Utrecht Leidsche Rijn	11,3	Clay	Bioswales, porous & permeable pavement	Non piped
Almere Homeruskwartier	8,6	Peat	Bioswales, porous & permeable pavement	Non piped

Table 3.2: *The characteristics of study sites in retrofitted areas. The table presents the landscape type, SUDS types and stormwater transport principle of the area.*

Study site	Soil condition	SUDS types present	Transport principle
Zwolle	Sand	Permeable pavement, facade gardens	Piped
Amsterdam	Peat	Bioswale, crates, above-ground storage	Piped
Gouda	Peat	Permeable pavement & crates	Piped
Tilburg	Sand	Facade gardens	Piped
Diemen	Peat	Above-ground storage, crates	Piped
Dordrecht	Sea clay	Underground storage	Piped
Rotterdam	Sea clay	Crates, permeable pavement, bioswales, water square	Piped
Nijmegen	Sand	Bioswale	Non piped

had three main goals:

- To collect general experiences from experts of working with SUDS;
- To identify what types of SUDS were applied in the municipality and why they were applied;
- To identify the failures that occurred in the implementation, construction and/or maintenance of the SUDS that were applied;
- To find out the experts opinion about the root causes that allow failures to occur in SUDS;

The interviews were semi-structured interviews, thereby leaving room for follow-up questions in case considered needed. An interview protocol was made, consisting of three parts: general questions, questions about the SUDS applied and questions about bottlenecks experienced. In this study a distinction has been made between two types of interviews:

1. *Inside:* Interview with the participant inside the municipality (recorded).
2. *Outside:* Interview with the participant outside during site visits (not recorded).

An overview of the type of interviews is presented in table 3.3.

3.1.3 Site visits

The goal of the site visits was the collection of cases of technical failures in SUDS, indicated by the experts. In this report the term 'case' is used for every single location

Table 3.3: *The overview of the interview and the site visit types for each study site*

study site	Interview location	Expert	Position	Date interview	Record?	Site visit	Date site visit
Waalsprong	Outside	#1	Projectmanager	21-02-2019	No	Yes (1)	21-02-2019
Meerhoven	Inside	#2	Projectmanager	22-02-2019	Yes	Yes (2)	27-02-2019
Nijmegen	Inside	#3	Senior consultant	01-03-2019	No	Yes (1)	01-03-2019
Gouda	Inside	#4	Team coordinator	29-03-2019	Yes	No	No
Leidsche Rijn	Inside	#5	Senior consultant	02-04-2019	Yes	Yes (2)	10-04-2019
Zwolle	Inside	#6	Consultant	15-04-2019	Yes	Yes (1)	09-05-2019
Homeruskwartier	Outside	#7	Senior consultant	17-04-2019	No	Yes (1)	17-04-2019
Dordrecht	Inside	#8	Maintenance advisor	02-05-2019	Yes	Yes (1)	02-05-2019
Dordrecht	Inside	#9	Consultant	14-05-2019	No	No	No
Diemen	Inside	#10	Policy officer	27-05-2019	Yes	Yes (2)	27-05-2019
Tilburg	Inside	#11	Director	04-06-2019	Yes	Yes (2)	04-06-2019
Amsterdam	Exsursion	#12	Hydrologist	06-06-2019	No	Yes (1)	06-06-2019
Rotterdam	Inside	#13	Consultant	04-07-2019	Yes	Yes	04-07-2019

where the expert indicated a failure in SUDS. Pictures were taken of each case. Only the cases that fell within the scope of the research were eventually added to the empirical observation data set. The cases were elaborated on shortly based on the information given by the expert and empirical research. All pictures presented in this research were taken with an Sony α6000.

There existed two types of site visits, as presented below. In table 3.3 the site visit types were indicated for each case study.

1. *Site visit with the expert:* Expert showed the SUDS and told at the failure locations a short summary about the system. In table 3.3 referred to as 'Yes (1)'.

2. *Site visit without expert:* Expert identified failures in SUDS during the interview held in the municipality. During interview the locations and system specifications were collected. Thereafter the site visit was carried out based on the locations that the expert provided. In table 3.3 referred to as 'Yes (2)'.

3. *No site visit:* When the study site did not consist of visible SUDS, not site visit was held. In table 3.3 referred to as 'No'.

3.2 Data validation

In order to guarantee the quality of the empirically collected data, two types of validation actions were taken:

1. For 8 of the 13 study sites, a second contact moment with the experts was held to discuss specific examples.

2. For all 13 study sites, the results are discussed with three professionals with expertise in the urban water sector.

Chapter 4

Research methodology: processing of the data

This chapter explains how the collected data was processed. There are two types of data, observation data and interview data, as explained in Chapter 3. This chapter is divided into three parts that were carried out in order to fulfil that aim. Figure 4.1 presents an overview of this chapter.

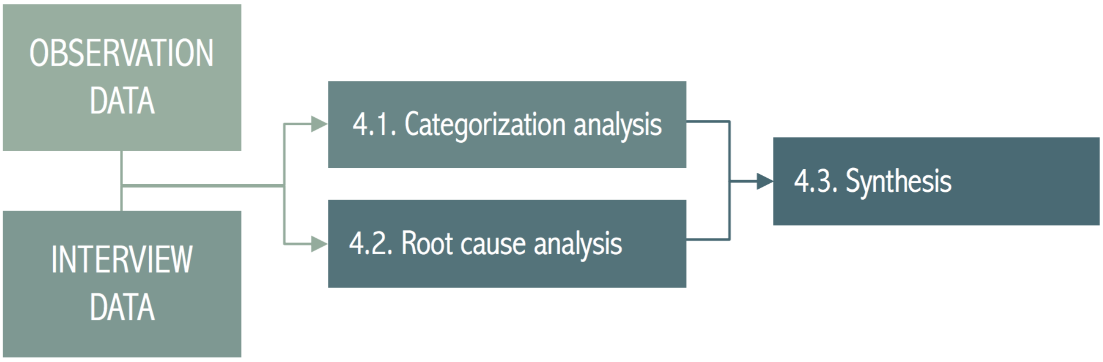

Figure 4.1: *Overview of the steps taken in processing the data*

4.1 Categorization analysis

To categorize qualitative empirical data a widely used strategy is coding. In coding, qualitative data is labelled and arranged in categories. The data can than be compared, both within and between categories. By coding the data, data is similarity-based ordered instead of the contiguity-based (Maxwell and Miller, 2008). To compare the failures in different types of SUDS, the coding strategy was used. Instead of 'coding categories' this research used the term 'label categories'.

The label categories were chosen based on literature and empirical research. The literature study showed that label categories 'Location' and 'Function' can categorize SUDS effectively. The number of label categories used was derived from what was thought necessary to properly represent all the important characteristics of the data. Based on the observations during the site visits, labels were iteratively added to the label categories, ensuring to describe the data set properly. The label categories chosen have been discussed with professionals to guarantee their added value. The label categories were subdivided into different characterisation themes:

1. **Physical characteristics**: describing the context of the technical failures in SUDS.

2. **Technical failure characteristics**: describing the technical reason behind the sub-optimal functioning of the SUDS and the impact it has on the environment.

In the following sections, these characteristics and the corresponding label categories will be discussed one by one.

4.1.1 Physical characteristics

These label categories represent the physical characteristics of the technical failures in SUDS, see figure 4.2. This resulted in the labels presented in table 4.2.

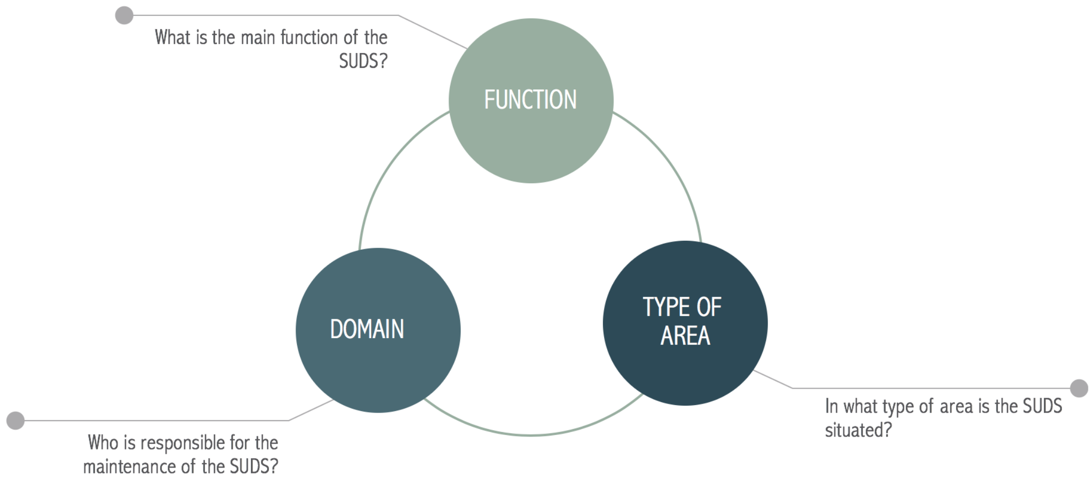

Figure 4.2: *Physical characteristics of SUDS*

Function

The label category 'function' is defined as the way in which the SUDS deal with storm water. Rainproof (2019a) used the filter 'Function' to categorize all measures with a certain solution type. They distinguished: *Retain and store water, transport water, infiltrate water, use water and build water robust.* Taking the work of Rainproof (2019a) as a guideline, the labels describing the general function of the SUDS are presented in table 4.2.

Domain

The label category 'domain' is defined as the person/persons responsible for the maintenance of the SUDS. In general a distinction was made between two parties: public and private parties. The list of responsible parties, collected from the site visits and interviews, is presented in table 4.2.

Type of area

The label category 'type of area' is defined as the building type of the area surrounding the SUDS. The case studies were carried out in two types of areas: newly developed areas and retrofitted areas. This distinction was made because it determines the way SUDS are integrated in the design.

Koekoek et al. (2017) identified 14 district types that are present in the Netherlands. According to them, district types make it possible to draw up and present generic climate adaptation measures for neighborhoods within the same typology. For this research, 6 of these 14 district types were found in the case studies. This provides information about the type of neighborhood where SUDS are located in.

Table 4.1: *District typology (Koekoek et al., 2017)*

District typology	Period	Characteristics
Historic downtown	pre 1940	High percentages paved surface, monumental green, 3-5 layers
Urban building block	pre 1940	Not always front garden, not always green, 4-8 layers
Working class quarter	1910-1940	Little green, single-family houses, 2-3 layers
Low-rise garden block	1945-1970	Open building blocks with a lot of green, single-family homes, 2-3 layers
High rise block	1945-present	More than 10 layers, constructed in a grid
"Cauliflower" block	1970-1990	Single-family houses with garden, lots of green, winding streets
Renewed	1990-present	Renewed existing building, high densities
Vinex	1990-present	Single-family houses in a row, semi-detached, detached, apartments

Table 4.2: *The physical label categories with corresponding labels*

Function	Domain	Type of area
Infiltration	Private (Residents)	Newly developed (Vinex)
Conveyance	Private (VVE)	Newly developed (Renewed)
Storage	Public (Municipality Green)	Retrofitted (Downtown)
	Public (Municipality Roads)	Retrofitted (Urban)
	Public (Municipality Water)	Retrofitted (Working-class)
	Water board	Retrofitted (Low-rise garden)
	Rijkswaterstaat	Retrofitted (High-rise)
		Retrofitted (Cauliflower)

4.1.2 Technical failure characterisation labels

The second set of label categories was used to characterize the technical failure occurring within each SUDS (4.3).

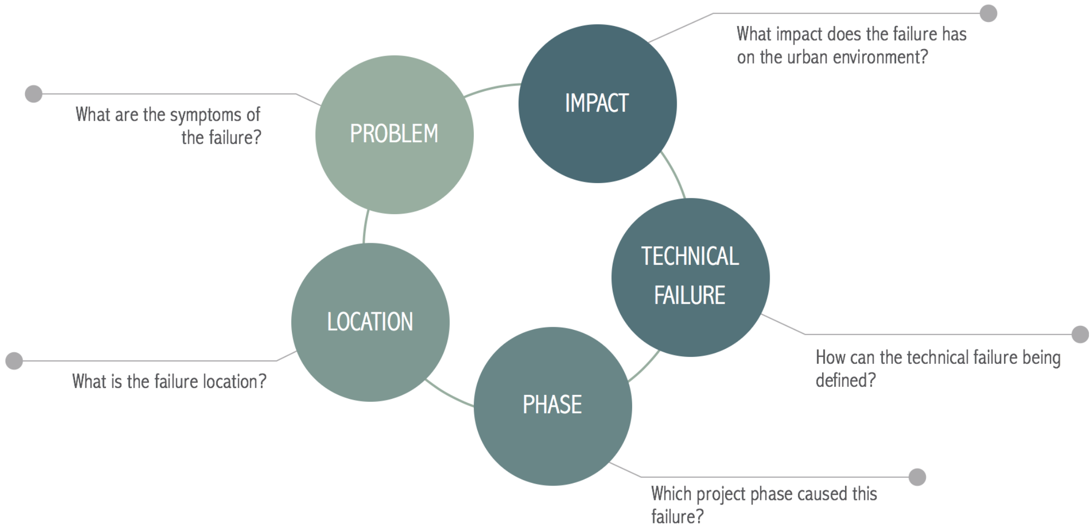

Figure 4.3: *Technical failure characteristics of SUDS*

Problem

The label category 'problem' was defined as the symptoms that are present due to the failure. The problems were defined based on empirical observations. If the problem was not visible it was based on the information from the experts. Different types of problems are distinguished, problems due excessive water, problems due to too little water, problems due to the quality of the water or problems that SUDS cause to their multifunctionality. The labels corresponding to the label category 'problem' are presented in table 4.3.

Impact

The label category 'type of impact' was defined as the type of impact the failure has on its surroundings. When a SUDS fails, the type of impact gives an indication of the magnitude of the problem.Van Riel (2011) came up with five categories of impacts for pluvial floods in the Netherlands. This study will make use of the impact types of Van Riel (2011) when describing the problem: *material impact, economic impacts, health impacts, emergency assistance impacts and discomfort*. In addition, the empirical research added the label *no direct impact*, as not every failure has a direct impact on its environment. The labels corresponding to the label category 'Type of impact' are presented in table 4.3.

Failure location

The label category 'failure location' was defined by the location in the urban environment where the failure is located. Figure 4.4 indicated the used failure location. SUDS are in some cases trans-boundary systems that connect two locations with each other. Therefore, the transition areas between the locations were also taken into account in this study. The labels corresponding to the label category 'failure location' are presented in table 4.3.

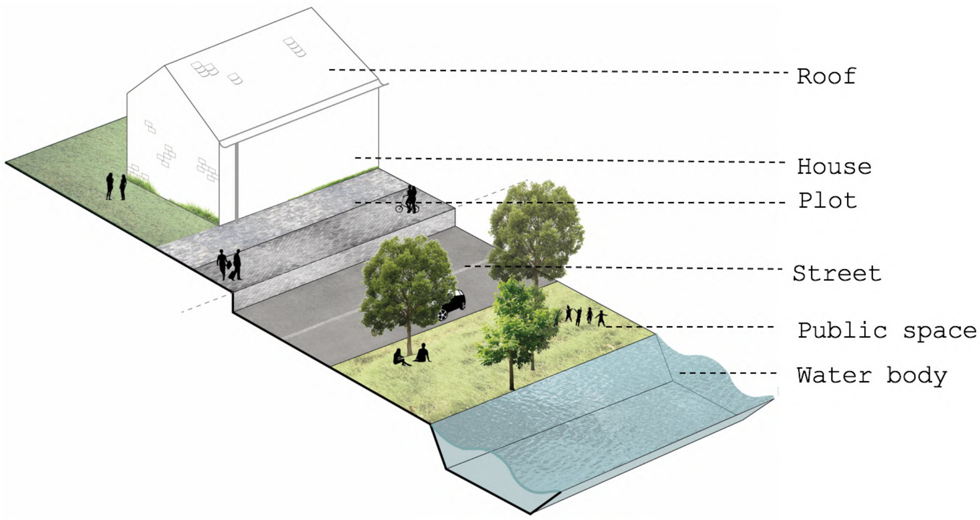

Figure 4.4: *The location indication of SUDS*

Technical failure

The label category 'technical failure' was defined as the technical reason why the system does not function optimally. The technical failures occurring with SUDS were in the first place based on literature on failures of specific systems, see Chapter 2.3. When the definition of the failures identified from literature were not able to describe the failure properly, new technical failures were added based on the information given by the experts and on the empirical observations. A description of every technical failures are presented Appendix 5.1.2.

Project phase

The label category 'phase' was defined as the project phase where the failure of the system originated from. To learn something about the failures of SUDS, it was important to identify when the failure was made. Therefore, three project phases where distinguished: *design phase, construction phase, user/maintenance phase* (see table 4.3).

Table 4.3: *Technical failure label categories with corresponding labels*

Problem	**Location**	**Type of impact**
Water nuisance	Roof	No direct impact
Water damage	House	Material impact
Water pollution	Plot	Economic impact
Causes nuisance in other domain	Street	Health impact
Minimal functionality of system	Open space	Emergency impact
Creating unsafe circumstances	Receiving water	Discomfort
	Neighborhood	
	Interface house to plot	
	Interface house to water body	
	Interface plot to street	
	Interface street to open space	
	Interface open space to water body	

Phase	**Technical failure**	
Design phase	**Literature:**	**Empirical research:**
Design/construction	Decreased walkability	Accessibility of drainage system
Construction phase	Pollution	Incomplete design
User/maintenance phase	Clogging	Limited freeboard
	Low maintanability	Outlet not fitted correctly
	Insufficient slope	Poor split binding
	Interference of obstacle	Wrong construction material
	Unsuitable subsoil	Local sagging
	Illicit connections	Wrong construction level
		Unfavorable roof design
		High groundwater level

4.2 Root cause analysis

This chapter presents the methods used for the root cause analysis. The goal of the root cause analysis was to find the underlying fundamental reasons for technical failures occurring in the SUDS. The root cause analysis first explains how root causes were defined in this study and secondly elaborates on how the root causes were derived from the data.

In literature, there is no general definition for a root cause analysis. Andersen and Fagerhaug (2009) explained that a root cause analysis is collective term for all approaches and techniques used to find the real cause of a problem. In this study, the root causes behind failures occurring within SUDS were identified based on the data collection of both the interviews and site visits. The definition process is discussed below. These root causes were used in the categorization analysis to describe the background of the failures. It was allowed to assign more than one root cause to cases.

4.2.1 Root cause definition

A root cause is defined as the underlying cause of the failure. By first observing the failure mode, determining the failure mechanisms the root cause could be found (Figure 4.5).

The root causes were found based on an iterative collection process, described in the following steps:

1. During the interviews, each expert was asked what he/she identified as the underlying reasons for technical failures occurring with SUDS. The key findings of

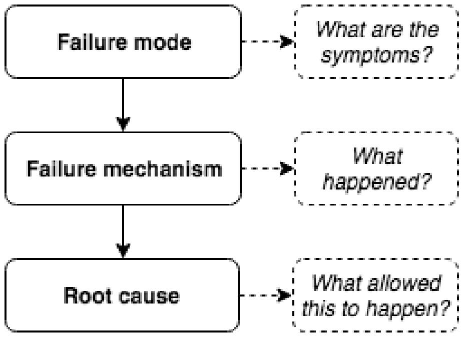

Figure 4.5: *Hierarchy in root cause failure analysis* (Post, 2016)

each interview were summarized. From the key findings of each interviews, various root causes were distinguished. These root causes were rephrased to one sentence to preserve the richness and interpretation of the interviews, but made them also usable as labels for the categorization analysis. The root causes found per case study were then combined to one list for all case studies together.

2. This list was checked on similarities. When two root causes from two different case studies were overlapping, they were rephrased as one root cause. By doing so, a optimized list of root causes for all case studies was obtained. The merged list was then applied on all cases, in order to see whether the root causes described the underlying reasons behind the failures well. This list was adjusted in an iterative way when it became evident that root causes did not describe the failures well.

3. This list was then discussed with one expert in the field to validate the identified root causes of step 2.

4.2.2 Relating root causes to literature

Uncertainty framework

As described in the literature study, Nieuwenhuis (2018) created a framework to classify the uncertainties that experts have experienced in the lifetime of integrated urban drainage systems, she composed a framework based on the two dimensions: the location of uncertainties (i.e. within the urban drainage system or between systems) and the nature of the uncertainty (i.e. technical, social, institutional).

This classification made by Nieuwenhuis (2018) is useful to classify the root causes behind technical failures of SUDS for two reasons:

1. The nature of root causes is useful to understand on which systems the focus must be placed. In solving the technical failures, do we have to focus on technology, the people or the processes?

2. The location of root causes is useful to understand the location where to focus on. Is their a lack of understanding about the internal technical system or do we have to focus more on the interactions between systems?

For this research the location of the uncertainties (internal, interface or external) described the location of the root causes well. However, the root causes defined in this research could not all be subdivided into one of the three natures (i.e. technical, social or institutional). The root causes were more a combination of the three. Therefore, it was allowed to make combinations between the three natures to describe the root causes (see figure 4.6).

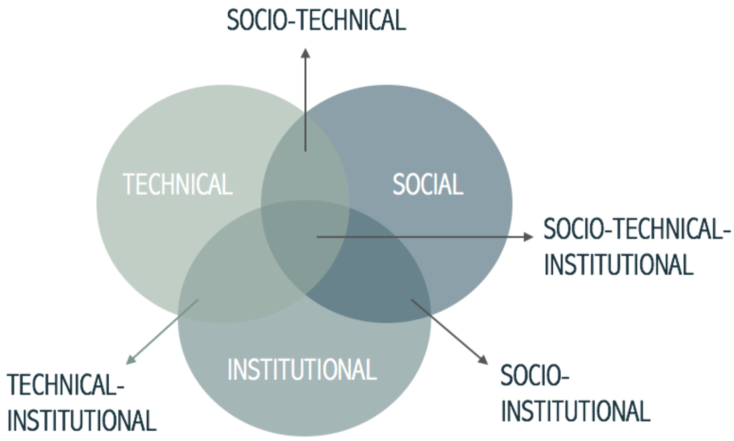

Figure 4.6: *The nature of the uncertainty subdivided in six categories: technical, socio-technical, social, socio-institutional, institutional*

4.3 Synthesis

This chapter describes the synthesis of the categorization analysis (section 4.1) and the root cause analysis (section 4.2). The goal of the synthesis was to connect and compare the results to draw synthesized conclusions.

The categorization analysis have led to the characterization of eight different label categories. The root cause analysis resulted in 13 one-phrased root causes. By combining both analysis, it can be seen how the both analysis relate to each other.

4.3.1 Root causes for system functionalities

The root causes for different functionalities of (e.g. conveyance, infiltration, storage) were combined. From this, the understanding could be created what the root causes are for certain SUDS functionalities.

4.3.2 Root causes for type of area

The categorization analysis showed in which 'type of area' the cases were located in. This knowledge was combined with the information about the root causes of the technical failures of these cases. From this, the understanding was created which root causes occur for different area types.

4.3.3 Root causes for project phases

It was investigated in which project phase the root causes occurred. The categorization analysis showed in which 'phase' the technical failures originates from. This was combined with the root causes in order to understand when in time the root causes occur.

Chapter 5

Results & Discussion

This chapter presents and discusses the results of the categorization analysis, root cause analysis and synthesis.

5.1 Categorization analysis

The categorization analysis resulted in the categorization of the 70 cases under eight different label categories. The results of the categorization analysis are presented in Appendix D. The results of the label categories are presented and elaborated on in the subsequent section.

5.1.1 Physical characterization

The results of the physical characterization label categories are presented in table 5.1. The numbers in the table represent the number of cases from the data set that correspond to that label. For example, there were 25 cases of SUDS with a conveyance function. In the subsequent sections the results of the label categories are presented and subsequently discussed.

Table 5.1: *The results of the three physical characterization label categories: function, domain and type of area. Numbers representing the number of cases (from the total of 70 cases) that represent that label.*

Function		Domain		Type of area	
25	Conveyance	15	Private (Residents)	33	Newly developed (Vinex)
31	Infiltration	1	Private (VVE)	5	Newly developed (Renewed)
14	Storage	8	Public (Municipality Green)	7	Retrofitted (Downtown)
		29	Public (Municipality Roads)	5	Retrofitted (Urban)
		13	Public (Municipality Water)	11	Retrofitted (Working-class)
		4	Water board	5	Retrofitted (Low-rise garden)
		0	Rijkswaterstaat	1	Retrofitted area (High-rise)
				3	Retrofitted area (Cauliflower)

Function

From figure 5.1 it can be seen that the cases are subdivided into three different function types: *conveyance (25/70)*, *infiltration (31/60)* and *storage (14/70)*. The observations showed that subdividing SUDS by function was a very useful method to compare different types of SUDS. It was seen that SUDS with the same functionality encounter the same types of technical failures. By combining the cases with the same functionality and discover what type of technical failures occurred, the main results of these three functionalities are itemized:

- **Conveyance:** The most common technical failures of conveyance systems are *Interference of an obstacle (6/25)* and *Insufficient slope (5/25)*.

(a) *Case #13: Interference of obstacle* **(b)** *Case #15: Insufficient slope*

Figure 5.1: *Two cases of technical failures in stormwater conveyance systems*

  Both technical failures are in line with previous work of Pötz and Bleuzé (2012) and Boogaard et al. (2006) as both stated that an insufficient slope and the interference of an obstacle could result in failures. This research contributes to previous research in identifying other technical failures for conveyance SUDS that where previously not mentioned in literature, namely: *an unfavourable roof design, local sagging and an incorrectly designed downspout outlet.* See chapter 5.1.2 for a visualization of these technical failures. Appendix C provides an explainanation of these technical failures.

- **Infiltration:** The most common technical failure of infiltration systems is *Clogging (9/31)*.

  This result is in line with previous research, as clogging was frequently mentioned as prominent failure of swales, permeable pavements and infiltration crates (Boogaard et al., 2006), (Scholz and Grabowiecki, 2007). Boogaard and Wentink (2007) concluded from interviews that many Dutch municipalities are not well aware of the clogging problems. This could be supported by the results from this study as *clogging* still often results in malfunctioning systems in practice.

  This research identified three other technical failures in infiltration systems that previously have not been reported on: *wrong construction materials, high groundwater levels and incomplete designs.* In appendix C these technical failures are further elaborated on.

- **Storage:** The most common technical failure of subsurface storage systems in this data set is *High groundwater level.* The most common technical failure of above-ground storage systems is the *limited free board.*

  Infiltration systems and subsurface storage systems are combined in most cases. When a failure occurred within the infiltration capacity, it was attributed to the function 'infiltration'. However, when a failure occurred within the storage functionality, the capacity to store stormwater, it was attributed to the function 'Storage'. Infiltration crates for example, both have an infiltration and an storage capacity. When the groundwater is so high that the infiltration crates are partly filled with groundwater, the storage function of the system is minimized.

Domain

The most cases in this data set are the main responsibility of the *street department (29/70)*. Only (8/70) cases the *green department* has the main responsibility.

The results show that most cases are located in the domain of the road department. This could be explained by the multifunctional capacity of roads in both serving as stormwater conveyance and infiltration. The interviews revealed that due to the implementation of SUDS, the responsibility for the collection and conveyance of stormwater is often shifted from the sewer department to the road and green departments. Additionally, the interviews showed that both street and green departments within the municipality are not familiar with this responsibility.

This observation is in line with research of Hoang and Fenner (2016). They described that the multifunctionality of SUDS in providing not only drainage function but also and ecological or build environment function, results in the involvement of various disciplines.

(a) *Case #3: Interface between private or public space*

(b) *Case #17: Interface between green and road department from the municipality*

Figure 5.2: *This figure shows two cases from the data set where the domain is questionable*

The observations revealed that for the interfaces between two areas, it is not always self-evident on which domain the actual failure occurs. For example in figure 5.2a, the curb between the sidewalk and the plot is the lowest point, causing stagnant water and water nuisance on the plot. The curb is part of the street, however the failure occurs at the plot. Every case was categorized by only one 'domain' type, although in reality some cases have shared responsibilities. This observation resulted in the understanding that in some cases, only one domain is not sufficient to describe the cases well.

Type of area

The data set consists of 38 cases in *newly developed areas*, and 32 cases in *retrofitted* areas.

The categorization showed an interesting difference between SUDS implemented in newly developed and retrofitted areas. SUDS that convey stormwater (i.e. above-ground drainage) were mainly been constructed in newly developed areas and SUDS that infiltrate or store water (i.e. permeable pavement, infiltration crates) were mainly constructed in retrofitted areas. This is in line with previous research, because Boogaard et al. (2006) explained existing urban areas usually do not have enough space for large above-ground systems, and therefore more often find solutions in the subsurface.

5.1.2 Technical failure characterization

In this section the technical failure characteristics are presented and discussed. Figure 5.2 presents the results.

Table 5.2: *Results of the technical failure characterization label categories: Problem, location, type of impact, phase and technical failure. The numbers correspond to the number to of cases (total of 70 cases) that represent that label. The technical failures are subdivided over technical failure adopted from literature or technical failures added by empirical research.*

Problem		Failure location		Type of impact	
29	Water nuisance	1	Roof	18	No direct impact
6	Water damage	2	House	9	Material impact
2	Water pollution	2	Plot	1	Economic impact
10	Causes nuisance in other domain	19	Street	4	Health impact
20	Minimal functionality of system	20	Open space	0	Emergency impact
3	Creating unsafe circumstances	1	Neighborhood	38	Discomfort
		4	Interface house to plot		
		4	Interface house to water body		
		10	Interface plot to street		
		5	Interface street to open space		

Phase		Technical failure			
35	Design phase		***Literature:***		***Empirical research:***
19	Construction phase	2	Decreased walkability	2	Accessibility of drainage system
15	User/maintenance phase	1	Pollution	6	Incomplete design
		10	Clogging	2	Limited freeboard
		2	Low maintanability	5	Outlet not fitted correctly
		5	Insufficient slope	2	Poor split binding
		10	Interference of obstacle	6	Wrong construction material
		2	Unsuitable subsoil	4	Local sagging
		1	Illicit connections	3	Wrong construction level
				1	Unfavorable roof design
				6	High groundwater level

Failure location

Failures are predominantly located on the *street (19/70)*, *open space (20/70)* and the *boundary between the plot and the street (10/70).* The locations of the failures specified per SUDS function are presented in figure 5.3.

Figure 5.3 shows that there exists a difference in the failure location of different SUDS functionalities. The failures of conveyance systems in this data set mostly occur at the interfaces between two types of areas. The observations revealed that such interfaces are often indicated by material changes (paved surface/vegetation), height differences (sidewalk/street) or physical structures (e.g. fence). For above-ground drainage, these changes can cause water to behave differently. In addition, the data showed that most failures occur on the boundary between the plot and street. This boundary represents the interface between private and public areas. Expert #5 explained that boundaries between private and public land are not designed in an integrated way, which can result in an unaligned design.

A comparison between the prominent failure locations of different types of SUDS systems have not been mentioned in previous research.

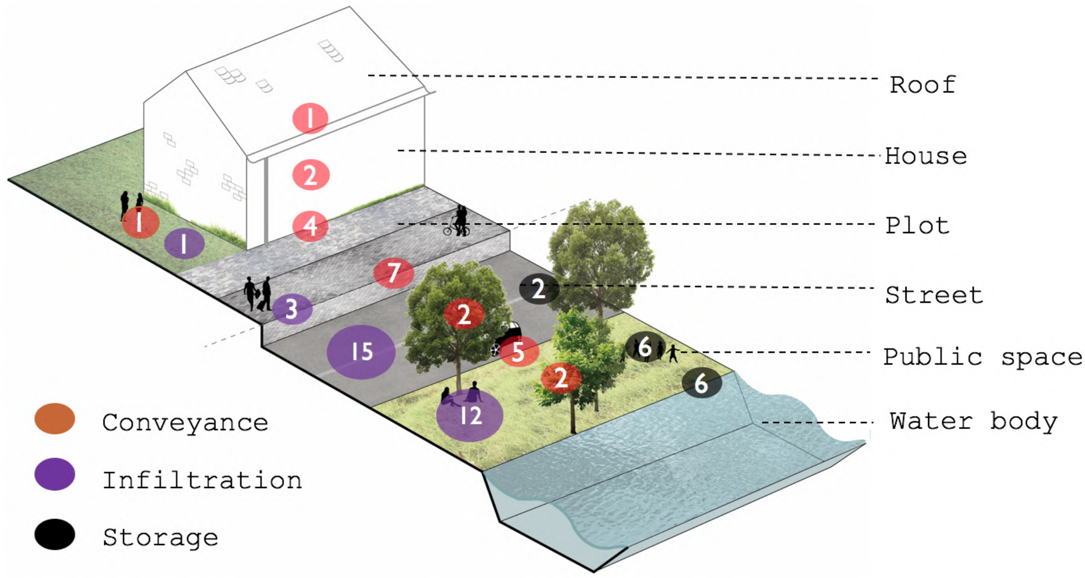

Figure 5.3: *The locations & number of the failures specified per SUDS function (e.g. conveyance, infiltration, storage)*

Figure 5.4: *Boundary house to plot*

Figure 5.5: *Boundary plot to street*

Figure 5.6: *Boundary street to open space*

Phase

The failures originate in (35/70) from the *design phase* , in (20/70) from the *construction phase* and in (15/70) from the *user/maintenance phase*.

This result shows that in all project phases failures occurred, suggesting that all project phases should be considered for creating successfully integrated SUDS. This result is supported by the research of Rijke et al. (2008), who concluded that all phases of the development process are important to successfully introduce innovative water system.

However, the results also show that most failures find their origin in the design phase. This result does not fully correspond to what experts mentioned during the interviews. First of all, experts explained that when a design is not fully specified, it leaves room for interpretation by constructors. As not all constructors are familiar with the construction of new systems, room for interpretation can cause incorrectly implemented systems, the experts explained. Secondly, the experts indicated that the knowledge level between designers and constructors is in some cases uneven. Therefore, they explained, should the design be more specified than usual, making it not multi-interpretable.

The results from the interviews imply that an unclear or unspecified design could lead to incorrectly installed systems in the construction phase. Moreover, this suggests both designers and constructors have a share in this. Therefore stating that most failures occur in the design phase, is in this case too generic.

Previous research does not specifically address the project phase where most technical failures in SUDS occur. However, Boogaard and Wentink (2007) presented guidelines, based on observations of infiltration systems in Dutch urban could contribute to a longer hydraulic lifetime.

Problems

Failures in SUDS result mostly in *water nuisance (28/70)* and *minimal functional SUDS (19/70)*.

(a) *Case #40: Minimal infiltration function* **(b)** *Case #50: Minimal storage function*

Figure 5.7: *Two cases from the data set that present SUDS with a minimal functionality*

A minimal functional system is defined by a system that poorly can perform its function (e.g. conveyance, infiltration, storage). The data shows that this problem emerged mostly for infiltration and storage systems. For example, when ground infiltration crates are partly laid below the groundwater table, the storage function is minimized. Moreover, when water cannot reach an infiltration surface due to the presence of an obstacle, the infiltration function is only applicable for direct rainfall and not for surface runoff. An example of this is presented in figure 5.7a, where the raised edge obstructs the water from flowing towards the façade garden. The water body in 5.7b has a minimal storage function due to the height level of the adjacent houses.

Technical failures

The empirical research resulted in the identification of 10 new technical failures. The site visits showed that technical failures are predominantly function specific, meaning that technical failures predominantly occur for certain types of SUDS functionality. In figure 7.1 and figure 7.2, a schematic overview is given of the technical failures occurring with above-ground conveyance, infiltration and storage systems are presented. By understanding the technical failures that occur in SUDS, future implementation of SUDS can be improved.

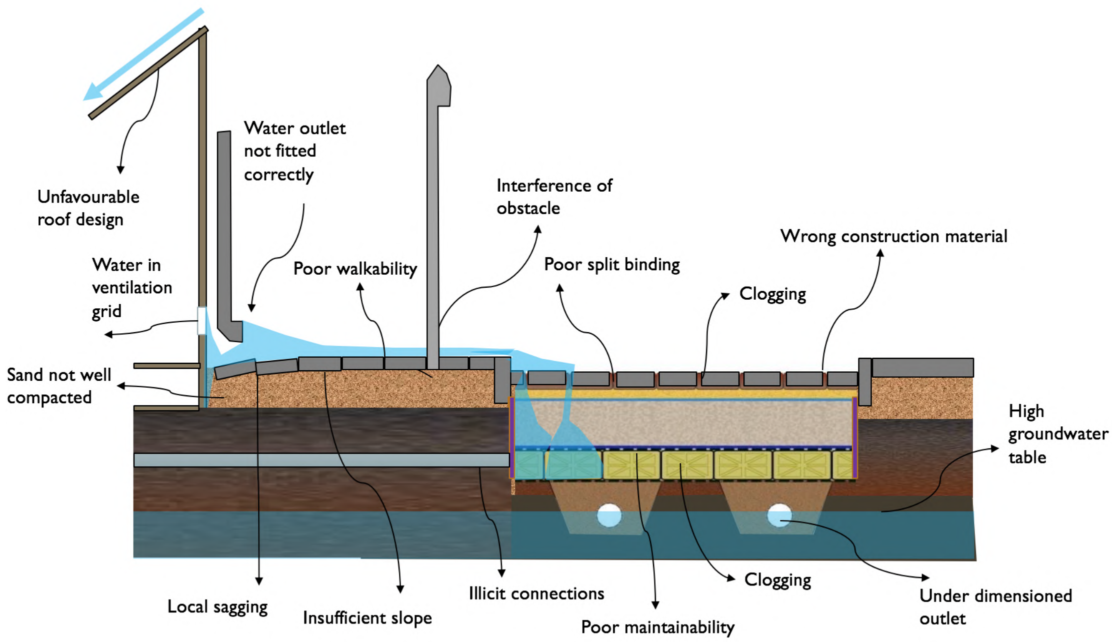

Figure 5.8: *Technical failures occurring on the street*

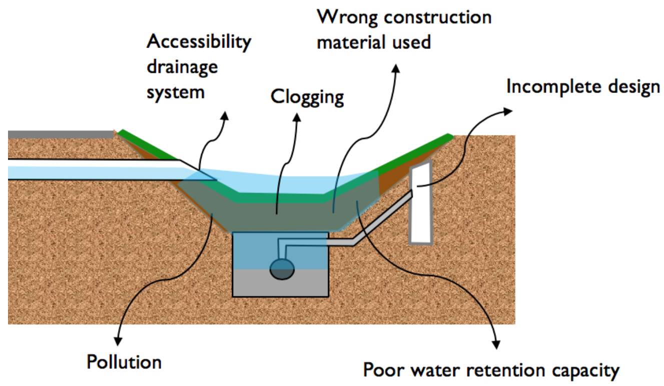

Figure 5.9: *Technical failures occurring on the open space*

5.2 Root causes analysis

In this section, the results of the root causes are presented. Because not all individual root causes could directly be related to literature, the complete set of root causes is compared to literature in the end of the section.

5.2.1 Identified root causes

The root cause analysis consists of three steps: 1) composing a list of one-phrased root causes collected from all interviews, 2) adjusting the list by merging overlapping root causes 3) validating adjusted list with an expert. The results of the first two steps are presented in table E.1 and E.2 in Appendix E.

The third step of the root cause analysis resulted into 13 root causes, presented below in table 5.3. Every root cause will be discussed in the subsequent sections. Table 5.3 furthermore represents the study sites where the root cause was visible in.

Table 5.3: *List of one-phrased root causes derived from interviews and site visits. When a root causes was visible in a certain study site, the box was coloured grey.*

Number	**Root cause**	**Eindhoven**	**Nijmegen**	**Gouda**	**Utrecht**	**Dordrecht**	**Zwolle**	**Almere**	**Diemen**	**Tilburg**	**Rotterdam**	**Amsterdam**
1	Embedded practices of the urban sector	■	■		■		■	■	■	■		
2	Unfamiliarity of integrating SUDS in spatial design		■		■							
3	Incomplete knowledge about the interactions of SUDS with urban systems	■	■	■	■		■					
4	Incomplete knowledge about the technical performance of SUDS					■	■				■	■
5	Unintended actual use of SUDS by humans		■		■	■	■	■				
6	Poor maintainability of SUDS				■		■	■				■
7	Undermine the functionality of SUDS by additional solution						■				■	
8	Poor communication between different actors	■	■		■			■				
9	Poor communication between phases						■				■	■
10	Fitting SUDS to unforeseen circumstances		■		■			■			■	■
11	Lack of experience in constructing SUDS		■		■		■	■				■
12	Unclarity about maintenance responsibilities for SUDS				■							■
13	Lack of knowledge how to maintain SUDS		■	■			■				■	■

Embedded practices of the urban sector

The root cause *Embedded practices of the urban sector* refers to the dominant and traditional knowledge, thinking or skills of the practitioners in the urban sector which leads to incorrect design or construction of SUDS. In figure 5.10 an practical case of this root cause is visible.

At seven study sites, experts mentioned this dominant thinking or skills of actors that led to failures in the design or construction of SUDS. This resulted in the formulation of six different root causes in the first step of the root cause analysis: 1) Traditional way of separating traffic from greenery and water bodies, 2) Traditionally constructing greenery with raised sites, 3) Traditionally constructing on one height level, 4) Traditionally constructing curb lower than street, 5) Traditionally constructing convex instead of concave streets and 6) The norm-oriented mindset in the Netherlands. All these root causes present a form of embedded practices. Therefore, in step 2 and 3 of the root cause analysis, these six root causes were merged into one root cause: *Embedded practices of the urban sector.*

Several experts indicated that in practice traditional measures (e.g. curbs, convex road) are so ingrained in the mindset of the urban sector that although changing the design, these traditional measures are in some cases still constructed. For example, expert #10 explained that although a concave road was drawn in the design drawing, a convex road was nevertheless constructed. The expert suggested that because the change from a convex to a concave road was not communicated explicitly, contractors found the sudden design change odd and constructed a convex road.

The results from the interviews suggest that the dominant thinking of, in this case constructors, leads to the misinterpretation or even mistrust of a design. This suggests that the traditional spatial design requires a simultaneous change in the dominant (cognitive) thinking of designers and constructor. The interviews revealed that this mindset change has not yet been fully achieved, resulting in some cases to wrongly constructed SUDS.

Figure 5.10: *Case #30: In this Case a façade garden is visible. Greenery traditionally have been separated from roads by raised sides (embedded practice). However, the raised sides in this Case make transport of water towards the facade garden impossible, whereby the facade garden can perform a minimal functionality.*

This is in line with the work of Brown and Farrelly (2009), who explained that the conservative mindset of urban water practitioners locks-out innovative solutions. Although this presents more a barrier to implementation, it shows that the way of thinking of urban practitioners is often focused on the traditional system. Brown et al. (2011) explained that actors can influence decision-making of large socio-technical systems; while these actors are shaped by a dominant path themselves. This is represented by Nieuwenhuis (2018) in the category of cognitive uncertainty in the uncertainty framework.

Unfamiliarity of integrating SUDS in spatial design

This root cause corresponds to the unfamiliarity of designers and constructors in adjusting the traditional spatial design to the design of SUDS. Due to this unfamiliarity, the designs of houses, streets and public spaces are not fully aligned with the design of SUDS.

In two study sites it was visible that SUDS where not correctly integrated in the spatial design, according to expert #3 due to the unfamiliarity of designers and constructors in adjusting the spatial design to the design of SUDS. The interviews revealed that the initial problem often starts in the design phase when a spatial design and SUDS design are not aligned (figure 5.11). Moreover, the experts explained that although the initial failure is made in the design phase, constructors also have a responsibility to compensate the failure during the construction of SUDS. Ideally, constructors would consult the designer and give feedback about the failure. However, as can be seen in figure 5.11, this often does not occur in practice.

(a) *Case #13: Structure blocking open gutter*

(b) *Case #7: Lamppost blocking open gutter*

Figure 5.11: *The technical failures resulting from the unfamiliarity of integrating SUDS in spatial design.*

The difficulties in allocation SUDS in spatial design is supported by the research of Zhang and Chui (2018), who appoint that because of LID-BMP-GI practices intervene with a large number of constraints in the urban environment, they should be carefully selected, designed and allocated within the urban environment. However, Zhang and Chui (2018) further investigates spatial allocation optimization tools (SAOTs) for LID-BMP-GI practices, and do not comment on effects of poor spatial allocated SUDS.

Incomplete knowledge about the interactions of SUDS with other urban systems

The root cause *Incomplete knowledge about the interactions of SUDS with urban systems* represents the lack of knowledge of designers and constructors about essentials parts of the interactions of SUDS with other urban subsystems (e.g. roads, greenery, surface water, traffic measures, lighting, electricity).

Several experts have indicated that the interactions of SUDS with other systems are hard to predict and cannot always be known in the design process because designers do not always have experience with particular systems. Expert #7 explained that a 2D design makes it difficult to see the interaction of different systems. The expert indicated that a 3D designs would help to discover interactions between systems in the design phase, however this development is not yet supported in every project phase. Figure 5.12 presents a case from the data set where traffic interactions with SUDS.

Previous research already pointed out that implementing SUDS in a complex urban environment results in new system interactions. Hoang and Fenner (2016) concluded that the implementation of SUDS/GI results in new interactions with subsystems, which could potentially pose negative impacts on the functioning of both SUDS and other urban components. de Bruijn and Herder (2009) explained that new interactions result

(a) (b)

Figure 5.12: *Case #29: The filling between the joints of permeable pavement bricks vanishes due to the load of cars and cleaning practices. There exists a lack of knowledge about the effects of other urban systems on the permeable pavement.*

in high system complexity, which makes the interaction between subsystems hard to understand and predict. Moreover, Zhou (2014) has described that one of the reasons for the insufficient performance of SUDS is misunderstanding of the interaction of SUDS with other systems.

This study contributes to former research in presenting practical cases of new system interactions that lead to technical failures in SUDS.

Incomplete knowledge about the technical performance of SUDS

The root cause *Incomplete knowledge about the technical performance of SUDS* represents the lack of knowledge about the internal technical processes that occur in SUDS.

(a) (b)

Figure 5.13: *Case #33: The permeable pavement with drainvast joints aims to infiltrate the stormwater falling on the street. After small rainfall events, water remains present for at least one hour. There existed an incomplete knowledge about the internal technical processes. It is expected that the slow infiltration can be caused by the connection between the split and the granulate layer.*

This root cause emerged in five different study sites. In the first step of the analysis, four different root causes have been defined: 1) Lack of knowledge about the performance of SUDS in practice, 2) Lack of knowledge of long term performance of SUDS, 3) Lack of information about impact of the subsoil conditions (only point information) on SUDS, 4) Lack of knowledge about the impact on the groundwater characteristics on the performance of SUDS, 5) Lack of monitoring and evaluating the performance of SUDS. In the second step of the analysis it became clear that these five root causes deal with the lack of knowledge concerning the technical performance of SUDS. Figure 5.13 presents a case from the data phase of internal processes that lead to malfunctioning SUDS.

The interviews revealed that little or no monitoring is carried out during pilot projects due to a lack of money, time and people resulting in a lack of knowledge about the internal technical performance and the reason for the failure. Unfortunately, nothing was actually learned from these pilot projects.

Expert #13 indicated that in the design process, sometimes limited information about the subsoil and its behaviour is available. When SUDS are then constructed in practice, the subsoil sometimes has slightly other characteristics than expected. Moreover, expert #13 explained that there exists a lack of experience from designers in understanding all the connections of SUDS with existing systems.

This suggests that there are in practice two things: 1) designers do not have the information they need to properly understand the internal processes SUDS, or 2) designers do not have the knowledge (too little experience and guidance) to properly understand the internal processes in SUDS. From the interviews it is suggested that in most of the cases it is a combination of the two.

That there often exists a lack knowledge about the internal processes in SUDS is supported by previous research. The practice-oriented research of Boogaard et al. (2006) shows that the technical knowledge about the systems is not yet complete and often too limited. With new knowledge it is possible to adjust the guidelines. Marlow et al. (2013) explained that predicting the performance and system behaviour of new innovative systems is difficult. Without engineering standards for the design of innovative systems this becomes an even more challenging job. The incomplete knowledge about the actual performance is presented in uncertainty framework of Nieuwenhuis (2018) by the 'actual performance uncertainty' in the category of technical uncertainty.

Actual use of SUDS

This root cause *Actual use of SUDS* represents the actual usage and unexpected interactions of SUDS by people.

Figure 5.14: *Case #8: Residents place flowerpot on the open gutter.*

In several cases residents used SUDS differently than intended. In the first step of the root cause analysis, two root causes were defined: 1) Unfamiliarity about the social impacts of the SUDS, 2) Lack of public understanding about the role of SUDS. Figure 5.14 presents a case from the data set.

The interviews revealed that residents often have limited knowledge about the functionality of SUDS. Due to this lack of knowledge, residents do not handle the systems as intended. The experts indicated that the municipality should inform residents better about the functionality of SUDS.

The lack of public understanding about their role in SSM, is recognized by Qiao et al. (2018) as one of the main barriers for the implementation of SSM. Moreover, Roy et al. (2008) states that the public understanding of their role in WSUD is often limited or incorrect.

Poor maintainability of SUDS

The root cause *Poor maintainability of SUDS* represents the fact the maintenance of SUDS is some times very complicated due to the inaccessibility and cleaning difficulties. This results in improper maintenance.

Figure 5.15: *Case #26: Vegetated swales are constructed in front of houses. However, these swales cannot be maintained properly, because mowing machines raise small stones that damage windows. Therefore, the maintenance becomes a time consuming and expensive matter.*

This root cause was visible at three study sites. Experts explained that the maintainability of SUDS is not always considered in the design process. Expert #8 explained that the involvement of operators in the design of new systems is very important to ensure the maintainability of SUDS, however this is in practice not always the case. According to expert #5, the inaccessibility of machines make that SUDS often cannot be properly maintained. This is shown in figure 5.15, a case from the data set.

The SUDS are often poorly maintainable is supported Boogaard and Rombout (2008), as they state that many infiltration facilities appear to be difficult to inspect and clean. How in the design take into account inspection wells and cleanability of the facility. They recommend to take into account the cleanability of the facility in the design phase.

Moreover, that the involvement of operators in the design phase is important for functional systems is mentioned in previous research of Moglia et al. (2011), explaining that the lack of involvement of operators in the decision stage can result in problems in the O&M (operation and maintenance) stage. However Moglia et al. (2011) studied decentralised systems instead of SUDS. Moreover, Rijke et al. (2008) stated that in order to prevent problems in construction and maintenance phases, early involvement of actors is important.

This suggests that to minimize problems in the operation and maintenance phase, operators should be involved in the decision making phase.

Undermine the functionality of SUDS by creating additional solution

The root cause *Undermine the functionality of SUDS by creating additional solution* represents the lack of trust in the functionality of SUDS in practice.

Due to the social uncertainties of actors involved, extra measures are constructed alongside to SUDS in order to guarantee the water drainage. By doing so, a double solution to a single problem is created, resulting in stormwater still ending up in the sewers. In figure 5.16 a case from the data set is presented where two drainage systems are constructed at the same location.

(a)

(b)

Figure 5.16: *Case #28: Next to the permeable pavement, a gully was constructed in order guarantee the drainage of stormwater. In order for the stormwater to reach the gully, the surface was laid with a small gradient towards the gully. Therefore, the water partly infiltrates via the permeable pavement and partly is drained via the stormwater sewer system.*

This relates to the research of Roy et al. (2008), where they explained that alongside with the construction of permeable pavements also gutters and curbs are installed due to standards. Roy et al. (2008) suggests that this problem arises due to insufficient engineering standards for SUDS. However, this study suggests that next to insufficient engineering standards, double solutions for a single problem are also a social problem caused by insufficient trust of decision makers in the functionality of SUDS.

Poor communication between different actors

This root cause corresponds to the lack of communication between different actors (e.g. municipality, project developer, water practitioner, architect, designers) during the design, construction and user phase of SUDS. This root cause also comprises the poor communication within one actor group (e.g. green, roads and sewer departments within municipality). Figure 5.17 presents two cases from the data set.

(a) (b)

Figure 5.17: *Case #60: Due to a lack of communication between the architect and municipality, this water body has no storage capacity although it was intended as such.*

The root cause emerged at four study sites. SUDS can be multifunctional systems and the development process involves actors from different disciplines. The interviews revealed poor communication between different actors.

Municipality and architect: Expert #2 explained that each actor has its own objectives, in some cases conflicting with the objectives of other disciplines. For example, the experts described that architects have certain ambitions, for example to achieve 'living by the water' the distance between the ground floor level of the house and the water level must be 15 centimeters. The municipality has other ambitions, creating a freeboard of 50 centimeters above the water surface as water storage. When these ambitions are not communicated and coordinated clearly in the design and decision making process, a design is created that only meets the requirements of one party. Expert #2 explained that this can result in undesired consequences and additional costs at a later stage.

This suggests that the conflicting interests, about in this case the functionality and aesthetics of a design, complicate the communication between the municipality and architect.

Municipality and project developer: Expert #6 described that in some cases the design of an area is allocated to two parties, for example a project developer and the municipality. Then it is very important that the interfaces between the two designs are well discussed and coordinated. This requires communication. Unfortunately, the expert mentioned, this communication and coordination does not always take place. Moreover, the interviews revealed that project developers are often only involved in the design and construction phases of newly developed areas. Therefore project developers often do seem to have interests in the long-term performance. The municipality however, is tied to the newly developed area for decades. This suggests that the fundamentally different interests of both actors often make it difficult to understand each other.

Municipality (road) and municipality (water): In addition, there can also be a lack of communication between or within disciplines of the municipalities. Expert #6 explained that a permeable paved street both functions as water infiltration facility and as transportation surface for traffic, involving both infrastructure and water drainage sectors. Each discipline has its own focus, which can lead to conflicting interests. The water sector wants large voids in order to meet the infiltration capacity, the infrastructure sector, however, wants small voids in order to minimize the collection of waste between the voids and ease the maintenance. The expert explained that the communication about these interests often leaks, resulting in a design with only the preferences of one discipline.

In previous research, the poor communication between actors involved is frequently mentioned as challenge, barrier or impediment for the widespread implementation of SSM (Roy et al., 2008), (Brown and Farrelly, 2009) and (Qiao et al., 2018). Communication between actors is often mentioned as a problem, according to Qiao et al. (2018), because of mutual mistrust.

Poor communication between different project phases

The *Poor communication between different project phases* refers to the lack of handover communication between the design, construction and user/maintenance phase.

Figure 5.18: *In the sketch design phase it was decided to place the bioswale 30 cm higher, creating a playground for children that would be flooded two or three times a year at most. Due to a new staffing in the subsequent design phase that did not know the old principles, it was thought that the bioswales should be laid deeper so that there would always be water in the bioswale. The residents complained because they were promised a playground.*

Expert #7 explained that several teams work at different stages of the development process. There is no continuity, because employees from the design phase are not present in the construction phase for example. Therefore, the optimal knowledge transfer between project phases remains an illusion in practice. Moreover, expert #6 also described that different people are involved throughout the process. When something has been decided in the start of the project with certain people, it remains difficult to anchor these decisions in the next phase, when other people are involved. According to expert #6, preserving important decisions throughout the entire process is a major challenge.

When comparing this to previous research, Rijke et al. (2008) concluded that handover periods can improve the quality of urban developments. Hand-over periods have the ability to reveal hidden failures.

This could lead to a recommendation to future projects in improving the communication between different project phases.

Fitting SUDS to unforeseen circumstances

This root cause represents the adjustment of SUDS layout or design due to circumstances that were not anticipated on in the design phase.

In the first step of the analysis, three root causes were identified at three different study sites: 1) Adaptation of system to temporary 'construction' situation, 2) Unforeseen changes in construction phase, 3) The phased construction of plots. All three root causes originate from unforeseen circumstances during the construction phase where the SUDS had to be adapted to.

Experts #1 described that during the construction phase of newly developed neighborhoods, many unforeseen changes occur. For example, in practice it happens height differences appeared to be insufficient for above-ground water transport. To ensure a properly functioning stormwater drainage system, the decision was made to construct a few stormwater pipes instead. However, expert #1 explained, installing a few stormwater pipes in an underground with only sewerage pipes, increases the chance of illicit connections.

The results of the interview suggest that unforeseen circumstances in the construction phase can results in sudden changes in the design, impacting the functionality of SUDS. This corresponds to previous research of Moglia et al. (2011), who explained that the knowledge available of the context in the design phase leads to a certain design with requirements. In the implementation phase, this is in some cases 'corrected' by a contractor with better knowledge of the context. This has impact on the functioning of the system in a negative or positive way. The study of Moglia et al. (2011) focuses on decentralised systems. This study contributes to this in providing the understanding that also for SUDS systems, unforeseen circumstances or context changes can result in system failures.

Lack of experience in constructing SUDS

This root cause represents the lack of experience of constructors in constructing SUDS.

As SUDS are relatively new developments, several experts described that constructors often have limited experience in the installation of new systems. Expert #6 explained that SUDS are complex systems that depend on many conditions, which are case and location specific. Due to a lack of experience, it is difficult for constructors to anticipate on these changing conditions. Expert #13 explained that in practice systems are in a slightly different way constructed from how it was intended by the designers. This does not immediately mean that the system does not function properly, but the system is not exactly constructed as how it was designed.

Supervisors from the municipality must ensure that the design is properly followed and installed in the correct manner. According to expert #5, the number of supervisors has been minimized due to cost saving reasons. Therefore, there is minimal control over the construction process. Moreover expert #7 explained that the municipality frequently hires externals for supervising practices representing the municipality, named the 'flexible shell'. Because these people were not involved in earlier stages, they do not have any background information about new types of systems. Therefore, expert #7 explained that it is difficult for them to detect failures during construction.

The interviews with experts suggested that constructors often have limited experience in the installation of SUDS. Therefore, SUDS are not always implemented as designed. Supervisors from the municipality are often scarce or under-informed. This suggests that failures are still prone to occur during construction.

This is supported by previous literature about failure occurring in decentralised systems. Moglia et al. (2011) named factors influencing the failure in the development process of decentralised systems. They named that the experience of a contractor is critical, because it can influence whether a system is implemented correctly as designed.

Unclarity about the maintenance responsibilities

This root cause refers to the fact that it is often unclear who is responsible for the maintenance of SUDS.

In the first step of the analysis two different root causes were defined at two study sites: 1) Unfamiliarity of responsible maintenance party and 2) Unfamiliarity of residents about the responsibility for maintenance. These two root causes both describe uncertainties regarding the maintenance of SUDS and were therefore combined.

The interviews revealed that since stormwater has traditionally been drained underground, many residents are unaware of their responsibility with regard to the care of stormwater on their property. Above-ground drainage systems make residents actively responsible for the maintenance practices of open gutters and downspouts. For example, expert #6 explained that residents do not know that they are responsible for the maintenance of open gutters and downspouts on their plot. Moreover, expert #6 indicated that in some cases it is questionable if the property is public or private (see figure 5.19).

Figure 5.19: *In this case there exists unclarity between the residents and the municipality who is responsible for the maintenance of the small bridges, crossing the bioswales.*

Additionaly, the interviews revealed that among departments in the municipality there also exists unclarity about their maintenance responsibility. Expert #5 indicated that the maintenance of SUDS requires the collaboration of multiple maintenance departments, due to their multi-functionality. If something fails, expert #5 explained, one of the three departments must provide measures or other maintenance practices. In practice it sometimes happens that everyone points at each other, expert #5 explained.

This suggests that due to the unclarity of maintenance responsibilities, maintenance practices are not sufficiently executed by residents or departments from the municipality.

Moglia et al. (2011) named the transfer of the systems to the operator, who needs clarity about the roles and responsibilities, a critical influencing factors for failures in decentralised systems. Moreover, Brown and Farrelly (2009) indicated that *Unclear, fragmented roles responsibilities* is one of the major barriers for the implementation of SSM. In addition, Nieuwenhuis (2018) referred to the *Unclarity about responsibiliy* as regulative institutional uncertainty. This study is in line with previous research.

Lack of knowledge how to maintain SUDS

This root cause refers to the lack of knowledge from maintenance department about how SUDS should be maintained.

In the first step of the analysis three different root causes were defined: 1) Lack of maintenance, 2) Maintenance budgets not adapted to required SUDS maintenance, 3) Lack of maintenance standards of SUDS.

Expert #7 indicated that new systems are not immediately known to the people responsible for the daily, and periodic maintenance of specific areas. Therefore, the knowledge how to maintain these new systems is not present. Moreover, the interviews showed that budgets for maintenance practices are based on the traditional, less expensive systems. According to Expert #7, permeable paved surfaces simply have different maintenance requirements (re-paving every 10 years instead of the regular once every 30 years). The expert explained that this therefore deserves the attention and training for the maintenance staff. If not, the expert stated, wrong assumptions can be made that decrease the functionality of SUDS. Additionaly, expert #8 indicated that it is very difficult for operators when a variety of small systems, which all have different maintenance need, are implemented all across the city.

(a) **(b)**

Figure 5.20: *Case #32: In this area porous pavement has been applied at streets and parking spots. When vegetation is constructed next to porous pavement, it happens that the porous pavement is blocked by leaves or dirt. This requires regular maintenance. However, operators are yet unfamiliar with the regular maintenance needs.*

Summarizing, the interviews revealed that required maintenance for new systems is not always known by the operators responsible for the maintenance. Therefore, wrong assumptions about the amount of maintenance can result in failures in SUDS. This is supported by the work of Boogaard and Rombout (2008), who concluded that Dutch municipalities are often not aware of the maintenance requirements of SUDS.

5.2.2 Relating root causes to previous research

In this section, it is investigated how the root causes identified in this study connect to previous research. Table 5.4 represents the root causes behind technical failures found and their link to previous research.

Table 5.4: *Root causes and their link to previous research*

	Root cause	**In line with research**
1	Embedded practices of the urban sector	(Brown et al., 2011), (Brown and Farrelly, 2009)
2	Unfamiliarity of integrating SUDS in spatial design	(Zhang and Chui, 2018)
3	Incomplete knowledge about the interactions of SUDS with urban systems	(Hoang and Fenner, 2016), (Zhou, 2014), (de Bruin et al., 2009)
4	Incomplete knowledge about the technical performance of SUDS	(Boogaard et al., 2006), (Marlow et al., 2013), (Hoang and Fenner, 2016)
5	Unintended actual use of SUDS by humans	(Roy et al., 2008), (Brown and Farrelly, 2009)
6	Poor maintanability of SUDS	(Moglia et al., 2011), (Boogaard et al., 2006), (Rijke et al., 2008)
7	Undermine the functionality of SUDS by additional solution	(Roy et al., 2008)
8	Poor communication between different actors	(Roy et al., 2008), (Brown and Farrelly, 2009), (Qiao et al., 2018)
9	Poor communication between phases	(Rijke et al., 2008)
10	Fitting SUDS to unforeseen circumstances	(Moglia et al., 2011)
11	Lack of experience in constructing SUDS	(Moglia et al., 2011)
12	Unclarity about maintenance responsibilities for SUDS	(Moglia et al., 2011)
13	Lack of knowledge how to maintain SUDS	(Boogaard and Rombout, 2008)

This study supports the observations on SUDS made by previous researchers ((Hoang and Fenner, 2016), (Zhang and Chui, 2018) and (Zhou, 2014)) in presenting practical cases in dutch urban areas where technical failures have arised. Moreover, this study supports the more practical based work of Boogaard et al. (2006) and (Boogaard and Rombout, 2008) within the Netherlands.

Additionally, this study reveals a link between transition literature to sustainable stormwater management ((Roy et al., 2008), (Brown and Farrelly, 2009), (Brown et al., 2011), (Qiao et al., 2018)) and technical failures occurring SUDS. Transition literature aims for the widespread implementation of SUWM and its infrastructure, however did encounter implemented SUDS. In ultimately striving for a water system with only SUDS, we first have to guarantee that those SUDS actually function conform standards Marlow et al. (2013). That is where this research adds to the transition literature, in providing empirical based evidence on root causes behind technical failures in SUDS. This understanding is used to improve future SUDS implementation, and make SUDS 'ready' for widespread implementation.

Uncertainty framework

The uncertainty framework of Nieuwenhuis (2018) is used to classify the root causes identified in this study based on two dimensions: the location (i.e. internal, interface, external) and the nature (i.e. technical, social, institutional). Figure 2.1 presents the results.

Nature of uncertainty: First of all, this table shows that failures stem from uncertainties in technical, social and institutional systems. Transition literature states that barriers stem mainly from the socio-institutional system ((Brown and Farrelly, 2009), (Qiao et al., 2018)). However, the classification reveals that we should not only focus on the institutional system but just as much on the social and technical system.

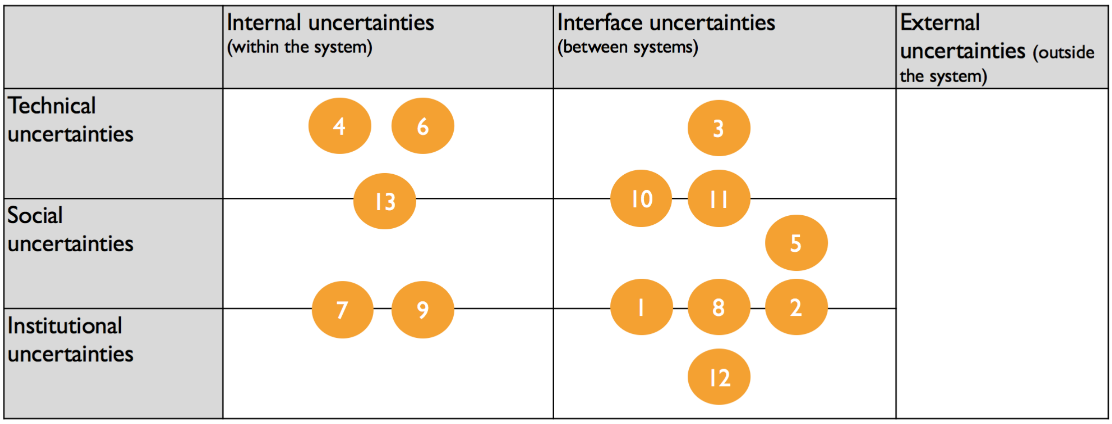

Figure 5.21: *Root causes subjected to the uncertainty framework of Nieuwenhuis (2018)*

In addition, the classification shows that in many cases the root causes stem uncertainties from a combination between two systems, socio-technical or socio-institutional. This implies that in solving these issues, the focus must be placed on both the technical and the social system or both the social and the institutional systems, as failures are not solely stemming from one system. Moreover, this implies that uncertainties in the technical and institutional system both show connections with the social system. The social system is closely related to the technical and the institutional system. This implies that there must be a focus to always involve and consider the people in new regulations and new technologies.

Location of uncertainty: The results show that root causes stem from uncertainties both within the system and between subsystems, however the majority occurs on the interface between systems. Previous research focused on the performance of SUDS in their context ((Huang et al., 2016), (Xie et al., 2019)), this research contributes to show that interfaces between systems are also very important to take into account, because most technical failures occur between systems.

Summarizing, it is demonstrated that the framework of Nieuwenhuis (2018) is applicable to classify root causes of technical failures in SUDS. This classification shows that root causes are visible in technical, social and institutional systems and are located both within and between systems. This makes it relatively difficult to identify a specific nature and location that requires extra attention in the future. However, in relating this to previous research, technical failures arising from socio-technical interface uncertainties are yet underexposed and could be characterized as special area for attention.

5.3 Synthesis

The goal of the synthesis is to combine the knowledge from the categorization analysis and the root cause analysis in creating one synthesized perspective. The synthesis was carried to understand the place and time where these root causes operate in better.

5.3.1 Root causes for system functionality

This section presents the combination of the root causes and the SUDS functionality; conveyance, infiltration or storage (Figure 5.22).

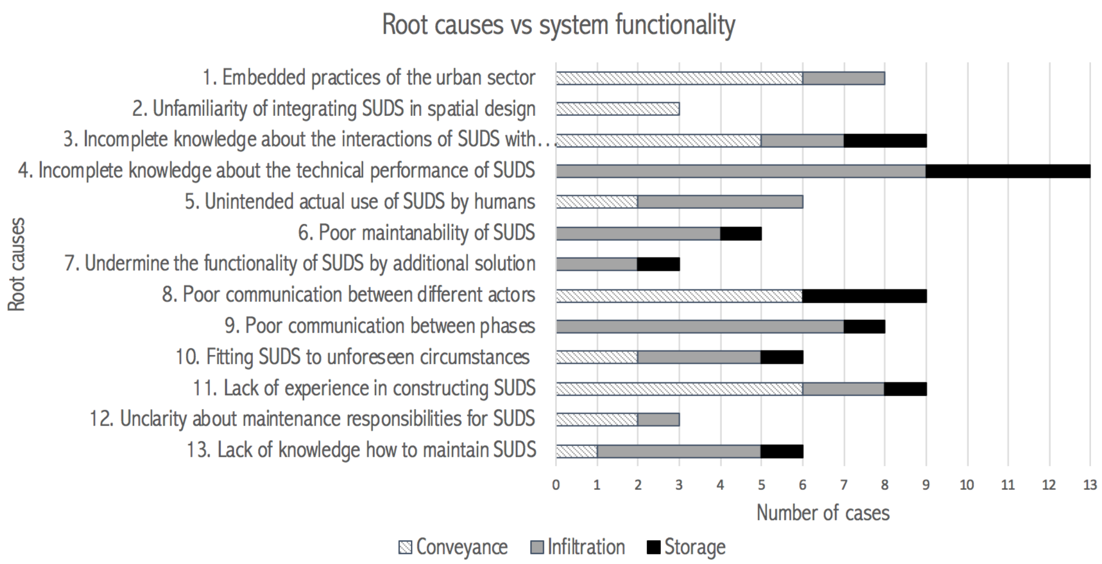

Figure 5.22: *A combination of the root causes and the SUDS functionality*

Figure 5.22 reveals that root causes behind technical failures are not system functionality dependent, as they occur for more system functionalities. However, it is clearly visible that the root causes occur more frequently in specific types of systems. For example, *Embedded practices* predominantly result in technical failures in conveyance systems, and *Lack of information about the technical performance* is the most common root cause for technical failures in infiltration systems. Two interesting results are gathered from this.

Firstly, figure 5.22 shows that the four main root causes for technical failures in conveyance systems are *Embedded practices of the urban sector*, *Incomplete knowledge about the interaction of SUDS with urban subsystems*, *Poor communication between actors* and *Lack of experience in constructing SUDS*. When looking back at the classification of root causes in the uncertainty framework (figure 2.1), the above-mentioned root causes for conveyance systems (root cause number 1, 3, 8 and 11) all stem from interface uncertainties. The site visits showed that above-ground drainage systems are located on the surface and therefore interact with many subsystems in the urban environment (e.g. roads, curbs, gardens, speed bump, lampposts). The interviews revealed that designers and constructors are not yet fully aware of these interaction of SUDS and subsystems. These results show that to minimize failures in conveyance systems, interfaces between SUDS and other subsystems deserve extra attention.

Secondly, figure 5.22 presents that the most common root cause of infiltration and storage systems is *Incomplete knowledge about the technical performance of SUDS*. The classification in figure 2.1) shows that this root cause arises from internal technical uncertainties. Expert #13 explained that the functionality of infiltration and subsurface storage systems depends highly on the type of subsoil. In the design process, expert #13 explained, sometimes limited information about the subsoil and its behaviour is available. When SUDS are then constructed in practice and the subsoil has slightly other characteristics than expected, technical failures may arise because the subsoil does not meet the requirements for storage and infiltration systems. This suggests that more research needs to be carried out on the internal technical processes in infiltration and subsurface storage systems.

Summarizing, the synthesis showed that for SUDS with a conveyance function, interfaces between SUDS and other subsystems deserve extra attention. Moreover, the synthesis showed that for infiltration and storage systems, more research needs to be carried out to the internal technical processes.

5.3.2 Root causes for type of area

In this section the combination of the root causes and the type of area (i.e. newly developed area or retrofitted ares) is presented. The synthesis is carried out to better understand if root causes occur for certain types of areas. The results are presented in figure 5.23.

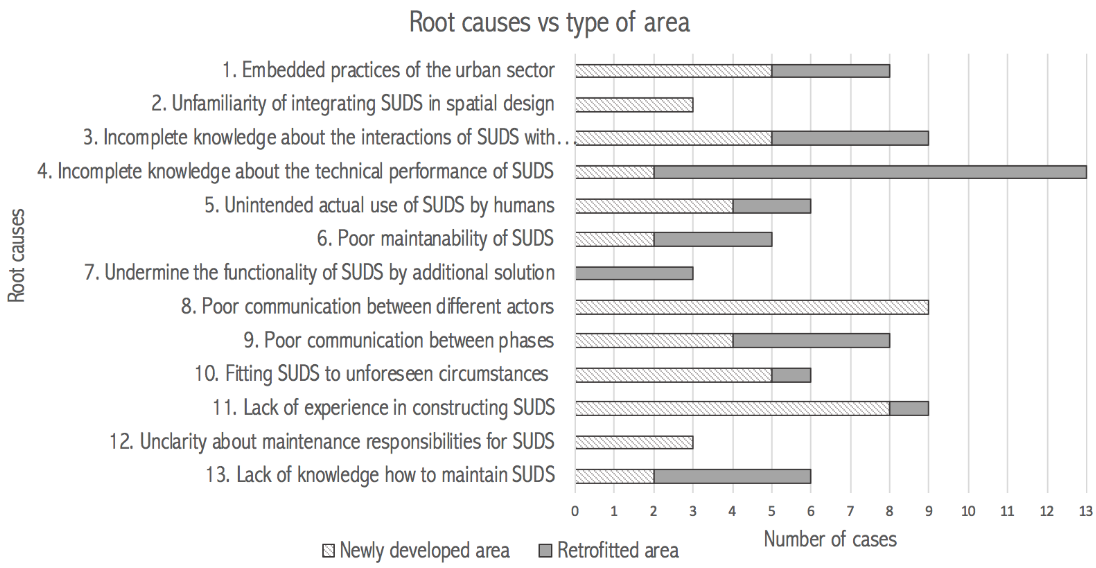

Figure 5.23: *A combination of the root causes and the type of area*

Figure 5.23 shows that particular root causes are more common for certain area types. For example, the root cause *Incomplete knowledge about the technical performance of SUDS* is more common in retrofitted areas. The categorization analysis revealed that infiltration and storage systems are in most cases retrofitted into existing areas. The interviews revealed that when SUDS are retrofitted in existing areas, the exact context of the area (i.e. subsoil conditions) are not always known in advance.

Moreover, the figure shows that *poor communication between different actors* only occurred for cases in newly developed areas. Many actors are involved in the decision making process of large Vinex districts (i.e. architects, project developers, constructors, urban water practitioners, municipalities) (Pötz and Bleuzé, 2012). The interviews revealed that because SUDS introduce new interfaces with other systems in the public space (i.e. streets, houses, electricity), new forms of communication between actors is required that did not exists for conventional piped UD systems. Therefore, it can be explained that poor communication between actors occurs more often in newly developed areas.

In retrofitted areas, *Poor communication between phases* more often lead to failures according to figure 5.23. Expert #6 explained that when SUDS are retrofitted in existing areas, the design is often made by the municipality, after which it is tendered to constructors. It often occurs, according to expert #6, that the limited communication between the design phase and the construction phase leads to a misinterpretation of the design requirements or the use of wrong materials. This suggests that the transition from the design to the implementation is crucial to successfully implement SUDS in retrofitted areas.

This table can serve as recommendation for future projects in identifying root causes that occur more often for that specific type of area.

5.3.3 Root causes for project phases

The root causes are combined with the project phases (i.e. design, construction and maintenance) were the technical failures originated from, presented in figure 5.24

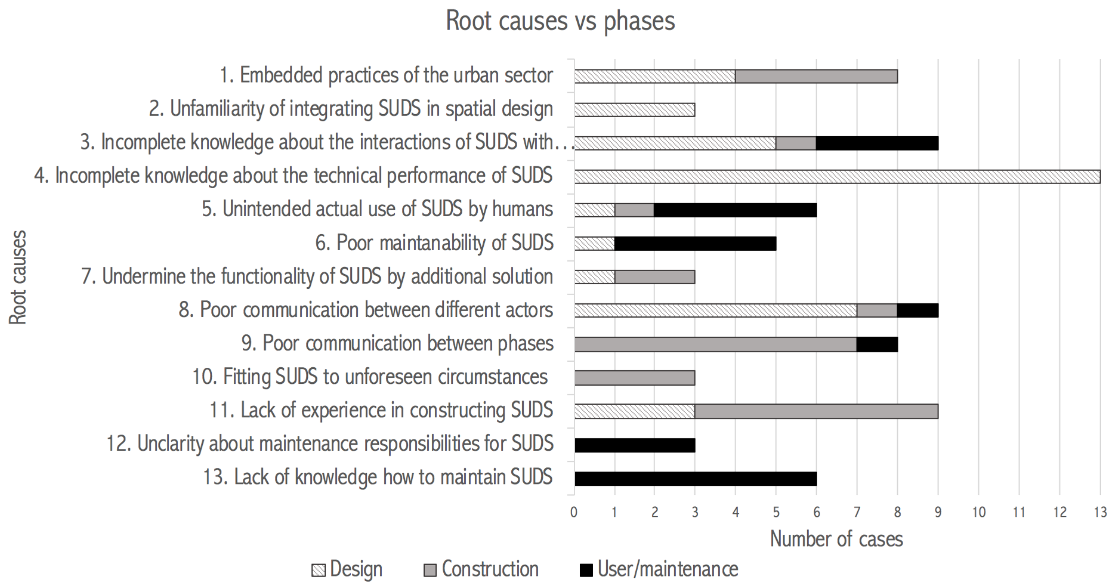

Figure 5.24: *The combination of root causes and the project phases*

First of all, table 5.24 shows root causes for all three project phases. This reveals that all three project phases are important for the development of new systems. For example, *Lack of knowledge how to maintain SUDS* leads in this research only to technical failures in the maintenance phase. This shows that even if SUDS are well designed and implemented, failures can still occur in the user/maintenance phase. In addition, since 8 of the 13 root causes appear in two or more project phases, root causes can in many cases not be attributed to just one project phase. For example, *Poor communication between different actors* can lead to failures in the design phase, as well as construction and maintenance phase.

This table provides information about which root causes are most likely to occur in a particular project phase. These insights can be used for future projects; where to pay attention to in every project phase.

- **Design phase:** Figure 5.24 presents that the root causes *Incomplete knowledge about the technical performance of SUDS* and *Poor communication between different actors* result in many cases to technical failures in the design phase. The classification of these root causes in the uncertainty framework show that these root causes stem from both internal and interface uncertainties and from technical and socio-institutional systems. The synthesis of the root causes and the types of areas showed that designing SUDS in newly developed areas entail other challenges than designing SUDS in existing areas.

  Combining these results reveals that when designing SUDS in newly developed area, to focus must be placed on sufficient communication between different actors to successfully align the SUDS design with other urban subsystems (i.e. roads, houses). When designing SUDS in retrofitted areas, the results show that the focus should be more on conducting research about internal technical processes, subsoil characteristics and the connection with the existing UD systems.

- **Construction phase:** The technical failures originating from the construction phase are often caused by *Embedded practices*, *Poor communication between phases* and *Lack of experience in constructing SUDS*. The classification in the uncertainty framework showed that these root causes stem mostly from the interfaces between systems and the socio-technical and socio-institutional systems.

  These results suggests that in the construction phase more attention must be paid to educate constructors about what new technologies entail and why new requirements are set.

- **User/maintenance phase:** Most dominant root causes for failures in the user and maintenance phase are *Lack of knowledge how to maintain SUDS*, *Poor maintainability of SUDS* and *Unintended actual use of SUDS by humans*. The classification of these root cause in the uncertainty framework generates two insights. On the one hand, the interviews revealed that operators lack knowledge about how to maintain SUDS, classified as internal socio-technical uncertainties. On the other hand, interviews revealed that residents are often unfamiliar with SUDS and do not handle the systems correctly, more a social interface uncertainty.

  This suggests that in the user/maintenance phase, more attention needs to explaining and guiding actors involved. Firstly, residents should be explained and guided in what SUDS entail. Secondly, operators should be educated in what type of maintenance is needed for SUDS and how they have to perform this.

To conclude, the synthesis of the root causes with the project phase showed that technical failures can occur in all project phases. Moreover, root causes cannot be attributed to just one phase, as they are visible in more than one phase. These insights can help defining which root cause actors should focus on in each project phase.

5.4 Limitations

This section discusses the limitations of the data collection, data processing and the results that were gathered from this.

5.4.1 Data collection

Interviews

The interviews that were conducted to collect information about the reasons behind technical failures in SUDS and the challenges in the development of SUDS could have induced biases; the answers could have been influenced by the role of the experts in the decision making process of SUDS.

Almost all experts that were interviewed (11/13) worked for the municipality. Since the municipality is an important actor in the design, construction and maintenance of SUDS, the answers of the experts to the questions about the reasons for technical failures could have been formed from a certain perspective. Moreover, the role of the experts could have caused them to withhold information because they are themselves involved in the process and cannot speak freely.

Due to the time limitation of the project only one expert was interviewed per study site; this could have reduced the validity of the results from the interview data. The experts said things about other actors in the decision making process (e.g. architects, constructors and project developers). However, due to time limitations other actors were not interviewed themselves.

Site visits

Site visits were conducted to collected cases of technical failures in SUDS. The cases gathered per site visits could show differences due to the interpretation of the definition 'technical failure', due to site-specific characteristics and available information per case.

Multifunctionality of SUDS: This study solely encountered the technical failures in SUDS with respect to their water functionality. Therefore, the technical failures do not present the complete functioning of SUDS.

Due to the multifunctionality of SUDS, their function can range from only a stormwater management function to a combination of a hydrological, ecological and built environment function. This research only focused on performance and technical failures regarding the water functionality of SUDS. The performance of other SUDS functionalities (e.g. ecological and built environment function) are also relevant for successful SUDS, however, were not taken into account in this study.

The interpretation of the definition 'technical failure': Although the definition of a 'technical failure' was discussed in advance with the experts, the interpretation of experts what indicated as 'technical failure' could have been different; The differences in interpretation could affect the cases of technical failures that were chosen by the experts in their municipality. For example, some experts showed cases where the technical failure of the system was actually visible, others showed cases of systems where something would go wrong in cases of sever rainfall events.

Available information per case: The information available about the technical failure and the underlying reason per case were different; this could have induced differences in the comparability between the cases. Some experts had an extensive explanation of the failure and the possible root cause. Other experts had heard stories about the systems from colleagues, but were not involved with the systems themselves. This causes differences in the amount of information available per case.

5.4.2 Data processing

Categorization analysis

The classification of observation data could have resulted in biases; classifications are in general made by subjective judgments causing the external validity to be doubted.

The time after implementation is not included in the classification of technical failure. Some systems were installed 20 years before the failure occurred and some systems were only installed for one year. The time after implementation could have influenced the failures that arise in these systems, however were not taken into account in the categorization.

Although the results about the technical failures in SUDS represent 70 cases, in some cases certain technical failure only were applicable in one case. For example, only the technical failure *'Unfavourable roof design'* was applicable to one case. The validity of the results could be reduced because of the small number of cases applicable to a certain technical failure. This makes the ability to generalize these results about certain technical failures to a broader context difficult.

Root cause analysis

The number of cases with the same root cause differentiated between a minimum of three cases and a maximum of 13 cases. The validity of the results could be reduced because of the small number of cases applicable to a certain root cause. This makes the ability to apply the results of the root cause analysis to a broader context difficult.

Chapter 6

Conclusions

In recent decades, sustainable urban drainage systems (SUDS) have been implemented in urban areas as an addition to, or as a replacement of, piped urban drainage (UD) system. In practice, SUDS do not always perform to an adequate standard due to technical failures. To ensure that future implementations of SUDS meet the set requirements and ultimately function as credible alternative to piped UD systems, the objective of this study is to identify technical failures occurring in SUDS and better understand their root causes.

In order to create this understanding, this study firstly aims to identify technical failures occurring in SUDS. Secondly, this study aims to better understand the underlying root causes. In the subsequent section, the conclusions of the most common technical failures and their root causes are presented. Thereafter, the conclusions about what these root causes imply are presented.

6.1 Technical failures in SUDS and their root causes

The site visits revealed that SUDS with the same functionality (i.e. conveyance, infiltration, storage) encounter the same types of technical failures. Therefore, the conclusions about the technical failure and their root causes are presented according to the SUDS functionalities (e.g. conveyance, infiltration and storage).

Firstly, the data shows that conveyance SUDS mostly fail due to *The interference of an obstacle (i.e. raised sidewalk, speed bump, lamppost)* and *An insufficient slope*. The interviews with experts revealed that *Embedded practices of the urban sector* and *Incomplete knowledge about the interaction of SUDS with urban subsystems* are most dominant root causes for failures. The observations show that interfaces between the house, plot, street and open space together with the interfaces between public and private domain are prominent failure locations for conveyance systems.

Secondly, the data reveals that infiltration systems fail mostly due to *Clogging*. This study identified three root causes of clogging: *Lack of knowledge how to maintain SUDS*, *Poor maintainability of SUDS* and *Incomplete knowledge about the technical performance of SUDS*. The interviews showed that next to maintenance shortages, there exists a lack of understanding from designers, constructors and operators about the internal technical performance of infiltration SUDS (i.e. infiltration capacity, subsoil characteristics, split binding behaviour) which can result in clogging.

Finally, the data shows that subsurface storage systems fail mostly due to *High groundwater levels*. The interviews revealed *Incomplete knowledge about the technical performance of SUDS* as dominant underlying root cause to this technical failure.

For SUDS with a surface storage function, the data revealed however that the most common technical failures is *limited freeboard*. The interviews reveal that because the surface storage systems have interfaces with adjacent structures (e.g. houses, buildings, parking garages) the design requires clear communication between actors.

6.2 Better understanding of root causes

This study shows that in every development phase of SUDS (e.g. design, construction and user/maintenance phase), technical failures can occur. Therefor, all three project phases are important to successfully develop SUDS. The root causes underlying the technical failures can be used to recommend future projects where to pay attention to and where to take action on in every project phase. This study reveals that in every project phase, more focus should be paid to provide training and guidance to designers, constructors, operators and users about SUDS. Moreover, this study reveals that when designing SUDS in newly developed areas, the focus must be placed on the communication between different actors to successfully align the SUDS design with other urban subsystems (i.e. roads, houses, infrastructure). When designing SUDS in retrofitted areas, the focus should be more on conducting research about internal technical processes, subsoil characteristics and the connection with the existing UD systems.

The 13 identified root causes provide insight in the processes that lead to technical failures in SUDS. The classification of the root causes according to the uncertainty framework of Nieuwenhuis (2018) reveals that root causes stem from uncertainties in technical, social and institutional systems and are located both within (internal) and between systems (interface). This study reveals that we should not only focus on the socio-institutional system but just as much on improving the technical system. Moreover, the interviews revealed that the implementation of SUDS in the urban environment present new interfaces between systems, disciplines and responsibilities. This study showed that these interfaces are critical and should be more thoroughly studied and understood.

6.3 The implications of this study

This study provides valuable insights into the technical failures occurring in SUDS and their underlying root causes. Since the introduction of SUDS in urban areas is a relatively new development, failures still occur regularly, causing malfunctioning systems, water nuisance and high costs. This study contributes to former research in identifying the technical failures in SUDS and their underlying causes. These valuable insights may prevent future projects from making the same mistakes, and may thereby minimize malfunctioning systems, water nuisance and high costs. Moreover, this research may ultimately contribute to better functioning SUDS, making them credible alternatives to conventional piped urban drainage systems. Nevertheless, further research is needed to systematically record the problems and weaknesses of SUDS.

Chapter 7

Recommendations

This study provides valuable information for future implementations of SUDS systems in dutch urban areas. Moreover, this study provides direction for further research. First, the recommendations for practical implementation will be described and thereafter the recommendations for further research will be elaborated on.

7.1 Recommendations for practice

The recommendations follow from both the discussion as the conclusion of this study.

1. The understanding which technical failures occur in implemented SUDS systems are helpful to improve future implementations of SUDS. Figure **??** presents a visualisation of the technical failures that occur for conveyance, infiltration and storage systems on the street. This knowledge could serve as recommendation for future projects that aim to implement SUDS where they must pay attention to.

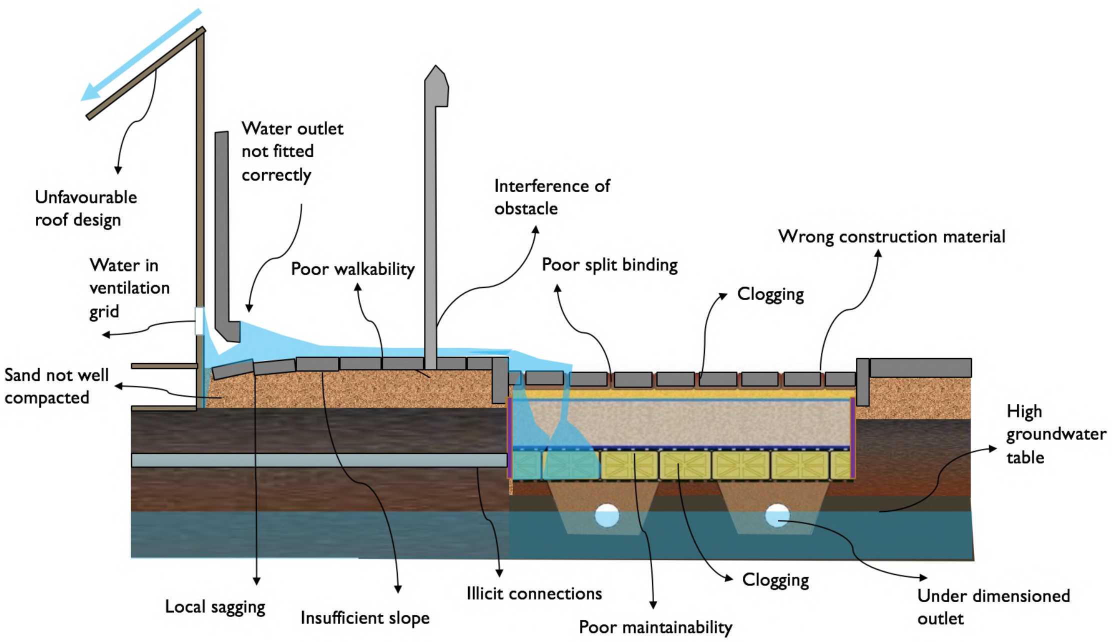

Figure 7.1: *Technical failures occurring on the street*

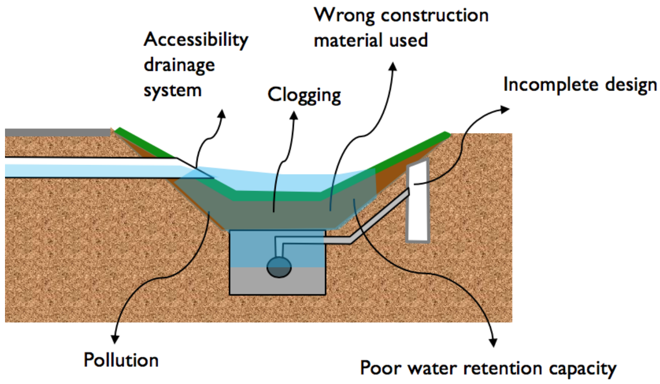

Figure 7.2: *Technical failures occurring in a bioswale*

2. The insights into the main location of technical failures, could help future projects in paying special attention to those locations in future projects. For conveyance systems specific, the interfaces between two systems and two area types are important.

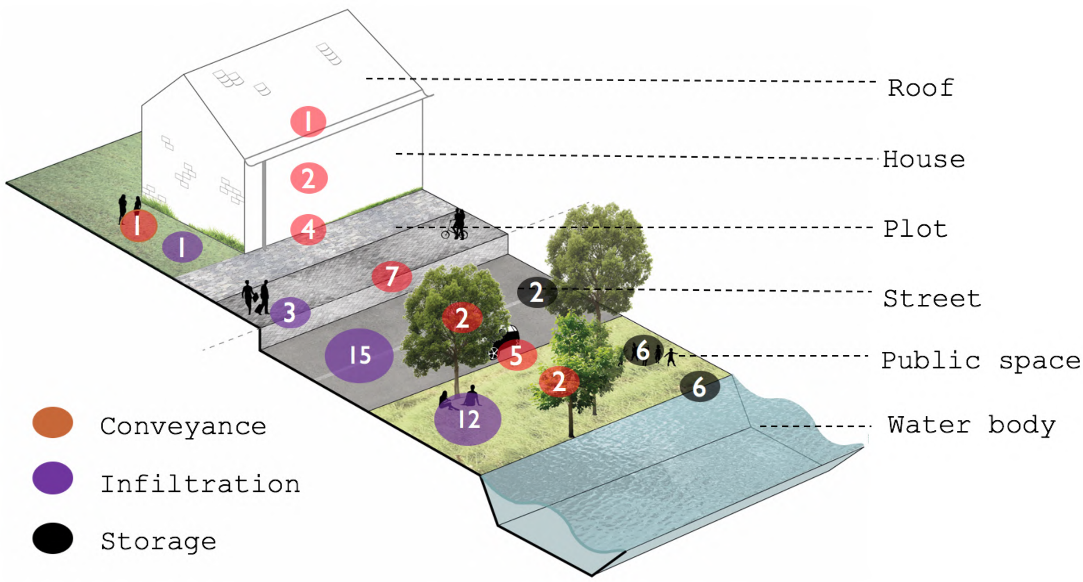

Figure 7.3: *The locations of where technical failures occur, specified per SUDS function (conveyance, infiltration, storage). Numbers indicate the number of cases from the data set that fail on that particular location.*

3. This study showed that in the design of SUDS of newly developed areas, the main root cause is *Poor communication between different actors*. This leads to the recommendation to focus on sufficient communication among actors involved in order to successfully align the SUDS design with other urban subsystems (i.e. roads, houses, water systems). This is however easier said than done. Therefore, for future research it is recommended to investigate what the critical factors are in the communication among actors in large newly build areas and how this could be improved.

4. When designing SUDS in retrofitted areas, the most common root cause behind technical failures found in this study is *Incomplete knowledge about the technical performance of SUDS*. Therefore, the recommendation is made that in the design process of infiltration and storage system in retrofitted areas, the subsoil- and groundwater characteristics should be studied closely before deciding if a system is applicable at a certain location. Moreover, more training should provided to educate designers in making the right decisions about which SUDS concepts to implement in existing areas.

5. The results showed that technical failures originating from the construction phase are often caused by *Embedded practices*, *Poor communication between phases* and *Lack of experience in constructing SUDS*. As these root causes all stem from social uncertainties, the recommendation is made that in the construction phase more attention must be paid to provide training to constructors about what new technologies entail and why they should be implemented. Moreover, the interviews revealed that a specific area of attention is the transfer of knowledge from designers to constructors. Experts explained that in many cases a design is handed over to constructors without further explanation about new requirements. Therefore, the recommendation is made to discuss the design specifications between the design and construction phase in more detail, to minimize the change of misinterpretation in the construction phase.

6. Most dominant root causes for failures in the user and maintenance phase are *Lack of knowledge how to maintain SUDS*, *Poor maintainability of SUDS* and *Unintended actual use of SUDS by humans*. This leads to the recommendation to involve operators in the decision-making process to ensure the maintainability of SUDS. In addition, it is recommended to better inform residents about SUDS and their functionality.

7.2 Recommendations for further research

1. Due to the multifunctionality of SUDS, their function can range from only a stormwater management function to a combination of a hydrological, ecological and built environment function. This research only focused on performance and technical failures regarding the water functionality of SUDS. However, the performance of other SUDS functionalities (e.g. ecological and built environment function) are also relevant for successful SUDS. Therefore, it would be recommended for further research to encounter the performance of all functionalities of SUDS (e.g. hydrological, ecological and built environment) to generate a complete picture of the performance of SUDS.

2. The identification of technical failures in SUDS could prevent future project from making the same mistakes. For further research, it would be recommended to define a strategy to systematically keep record of the weaknesses and failures occurring in SUDS, creating a platform where designers, constructors and operators can learn from mistakes made in the past.

3. Due to time limitations, only one expert was interviewed per study site. In 11 out of the 13 cases this expert worked at the municipality. These experts explained their vision on the truth and elaborated on the behaviour of other actors in the decision-making process (e.g. architects, project developers, constructors). For

further research, it would be recommended to also interview the other actors (e.g. architects, project developers and constructors), in order to increase the external validity of the study.

4. The cases in this study do not have the same amount of background information. For some cases, many background documents (e.g. design drawings, building specifications) was available, however for other cases not. Therefore, for this research the background documents could not be used. For future research, it would be interesting to examine less cases, however then only cases with a lot of background information. By doing so, information about the exact moment of the failures (more specific than project phase) could be found.

5. This study focuses on the technical failures of different implemented SUDS in Dutch urban areas. However, this study did not cover all types of SUDS present in Dutch urban areas. For further research, it is recommended that more types of SUDS (e.g. green roofs) are added to data set, in order to create an overview of all types the SUDS present in the Netherlands.

6. Previous research about the performance of SUDS is mostly dedicated to infiltration systems (e.g. bioswales, porous and permeable pavement, subsurface infiltration crates). Yet, little has been written about the performance of above-ground drainage of stormwater. This study provides insight in the performance of above-ground drainage systems. Further research could further enhance this knowledge, by actually improve the design of above-ground drainage systems.

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Appendix A

Dutch sustainable urban water management practices

This chapter will shortly describe the policies and regulations present in the Netherlands that deal with sustainable urban water management.

A.1 Municipal water tasks

Each municipality in the Netherlands have the duty of care of water tasks including the responsibility for the efficient collection and processing of run-off rain water on the basis of article 3.5 from the Water law (Waterwet, 2018). The municipal sewerage plan (GRP) describes how the municipality performs or intends to carry out its duties. The municipality must prepare this plan on the basis of the Environmental Management Act. Municipalities have a lot of freedom when it comes to the interpretation of these policies, therefore GRPs vary greatly between municipalities. The close relationship of the drainage system with the water system, makes close coordination with the water board essential.

The primary goals of the municipal water tasks are stated as following VNG (2018):

- Protecting public health;
- Contributing to clean and clear drinking water;
- Ensuring dry feet;
- Ensuring a good living environment.

A.2 Delta program

The delta program is the municipal agreement for climate adaptation in the Netherlands. At the end of 2014, the central government established the Deltaprogam as a policy in the National Water Plan. The umbrella organizations of the provinces, the water boards and the municipalities declared their commitment to the chosen approach by signing the Delta Program Management Agreement, with the agreement to promote the delta decisions and strategies and capture them in their own plans (IenW, 2017). As a part of the Delta program, there is the Delta Plan on Spatial Adaptation (DPRA). The DPRA is a joint national plan for the responsible municipalities, water boards, provinces and central government with concrete actions and objectives. As presented in A.1, DPRA comes up with measures that can be taken in the neighborhood to increase adaptation.

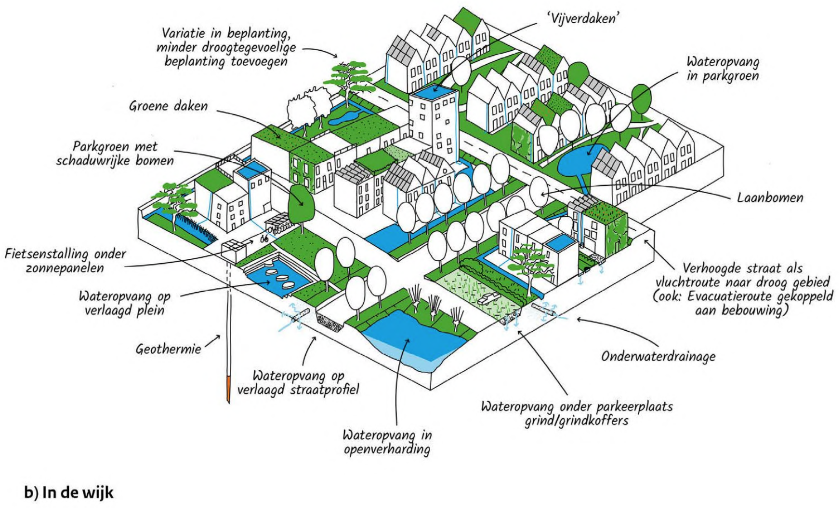


Figure A.1: *Measures for climate adaptation (IenW, 2017)*

A.2.1 Climate stress test

As part of the DPRA, it has been agreed that all governments carry out a stress test by 2019 for the four climate themes: flooding, heat, drought and flooding. A stress test identifies potential vulnerabilities to climate issues within an area.

A.3 Environment and Planning Act

The Environmental and Planning Act aims to simplify and bundle all laws and regulations in the field of the urban environment, is expected to enter into force in 2021 (Rijksoverheid, 2019). The goals of the Environment and Planning Act is to:

- better coordinate the various plans for spatial planning, environment and nature;
- stimulate sustainable projects (such as wind farms);
- give municipalities, provinces and water boards more room to adjust their environmental policy to their own needs and objectives.

The Environment and Planning act will support different sectors (infrastructure, building and water) to combine their interest and work together. From a water perspective this means a better integration of both the water processes and spatial planning and designing of the urban areas.

Appendix B

Barriers for implementation

Table B.1: *Impediments to sustainable stormwater management (Roy et al., 2008)*

No.	***Impediment***
1	Uncertainties in performance and costs
2	Insufficient engineering standards and guidelines
3	Fragmented responsibilities
4	Lack of institutional capacity
5	Lack of legislative mandate
6	Lack of funding and effective market incentives
7	Resistance to change

Table B.2: *Barriers to sustainable urban stormwater management (Brown and Farrelly, 2009)*

No.	***Barrier type***
1	Uncoordinated institutional framework
2	Limited community engagement, empowerment & participation
3	Limits of regulatory framework
4	Insufficient resources (capital and human)
5	Unclear, fragmented roles & responsibilities
6	Poor organisational commitment
7	Lack of information, knowledge and understanding in applying integrated, adaptive forms of management
8	Poor communication
9	No long-term vision, strategy
10	Technocratic path dependencies
11	Little or no monitoring and evaluation
12	Lack of political & public will

Table B.3: *Challenges to the implementation of sustainable stormwater management (Qiao et al., 2018)*

No.	***Barrier type***
Actors	Unclear leadership & responsibilities Difficult to engage stakeholders & difficult to cooperate with different stakeholders Lack of public understanding of their role in stormwater management Lack of institutional capacity Lack of experienced expertise Disagreement with the effectiveness or the means of achieving planning goals
Resources	Lack of funding Lack of evidence on what SSM costs and SSM efficiency Lack of effective market incentives Lack of space Lack of knowledge Lack of staff and time
Rules of the game	Lack of incorporation of SSM in legislative mandates Lack of SSM standards
Discourses	Fragmented envrionmental stakeholder network Perceived risk in cost and performance Lack of identifiable environmental values Lack of awarenes of the adaptability of SSM technologies and policies Engineering culture and resistance to change Lack of congruence between political and hydrological considerations

Appendix C

Description technical failures

Table C.1: *Description of technical failures mentioned by previous research*

Technical failure	Descriptive explanation	Literature
Decreased walkability	*When streets are no longer safely accessible for pedestrians*	(Boogaard et al., 2006)
Pollution	*When pollutants are introduced into the natural environment*	(Geiger et al., 2009)
Clogging	*When the pores of an infiltration media are blocked*	(Boogaard and Wentink, 2007), (Xie et al., 2019), (Scholz and Grabowiecki, 2007)
Low maintanability	*When the maintenance of SUDS is complicated by inaccessibility or limited inspectable*	(Boogaard et al., 2006), (Boogaard and Rombout, 2008)
Insufficient slope	*When the slope of the surface is not sufficient for stromwater conveyance*	(Pötz and Bleuzé, 2012)
Interference of obstacle	*When an obstacle interferes with the conveyance or temporary storage of stormwater*	(Rainproof, 2019b)
Unsuitable subsoil	*When the subsoil is not able to allow water infiltration or water retention*	(Boogaard et al., 2006)
Illicit connections	*When a wastewater sewer is connected to a stormwater sewer or vice versa*	(Boogaard and Rombout, 2008)

Table C.2: *Description of technical failures found by empirical research*

Technical failure	Descriptive explanation
Accessibility of sewer	*When the opening or outlet of a drainage system is not properly closed, making it accessible to people*
Incomplete design	*When a crucial part of the system is not constructed in practice*
Outlet not fitted correctly	*When the outlet of a systems is located at the wrong place*
Poor split binding	*When the binding material between tiles disappears*
Wrong material	*When the wrong construction material is used for a part of the system*
Local sagging	*When the tiles are subsided by above-ground drained stormwater*
Wrong construction level	*When a system is not installed at the correct construction height*
Unfavorable roof design	*When the roof design makes the drainage of stormwater inefficient*
High groundwater level	*When the groundwater is so high that it impedes the infiltration or storage of stormwater*
Limited freeboard	*When a structure minimizes the freeboard of a storage system*

Appendix D

Results categorization analysis

First the results are presented in an overview table. There after single example with a picture is presented.

	F.1	F.2	F.3
Description	Stormwater from the roofs and streets is transported via above-ground drainage towards a central bioswale with a large storage capacity of 24 mm. When the streetside of the bioswale is not maintened suffienctly, the grass becomes higher than de street. In this case the stormwater cannot reach the bioswale easily because it is blocked by the high grass.	In this park stormwater from roofs and streets is transported below ground by IT-sewers towards a central bioswale in the middle of the park. Stormwater first can infiltrate into to the ground through an IT-sewer and when it rains heavily the stormwater is transported to the bioswale. However, the opening of this pipe is large. Kids who play in the bioswale can crawl into the opening of the pipe. This can cause very dangerous situations. In order to reduce this problem, the municipality placed bars infront of the opening of the pipes.	In this street stormwater from roofs is transported above ground, via the front yard of the houses, towards the permeable pavement street where the stormwater can infiltrate. The curb is constructed lower than both the front yard and the street, which makes it the lowest point. When the water flows from the open concrete guttur towards the sidewalk, the water flows back into the garden. The reason behind this problem is the fact that constructors trationally place curbs lower and than the streets because streets tend to subside and the curbs do not. Because of these height differences the stormwater cannot easily flow to the permeable pavement en causes water nuisance in the front yards of the residents.
Function	Conveyance	Conveyance	Conveyance
Domain	Public (Municipality Green)	Public (Municipality Water)	Private (Residents)
Area type	Newly developed area (Vinex)	Newly developed area (Vinex)	Newly developed area (Vinex)
Problem	Water nuisance	Creating unsafe circumstances	Water nuisance
Location	Boundary street to open space	Open space	Boundary plot to street
Type of impact	Discomfort	Health impact	Discomfort
Technical failure	Interference of obstacle	Accessibility of drainage system	Insufficient slope
Failure occurred	User/maintenance phase	Design phase	Construction phase
Root cause	Unclarity about maintenance responsibilities for SUDS	Unintended actual use of SUDS by humans	Embedded practices of the urban sector
Root cause	Poor communication between different actors		
Picture			

Figure D.1: *Cases 1-3*

F.4	F.5	F.6	F.7
Stormwater is above-ground drained via a lowered open gutter in the street. It can be seen that the tiles surrounding the opening of the downspout have sagged. This is due to the fact that the water washes away the sand under the tiles. On the interface between the house and the street, sand can not be well compacted. Because this sand is less compacted, it can subside in the user phase.	In this street stormwater from roofs is transported above ground towards small bioswales infront of the houses. In this situation it can be seen that the gradient of the open concrete gutter, constructed to transport the water from the downspout towards the bioswale, is directed to the wrong side.The reason behind this is the local subsidence.	In this street stormwater from roofs is transported above ground towards small bioswales infront of the houses. In this situation it can be seen that the open concrete gutter, constructed to transport the water from the downspout towards the bioswale, is not directed towards the bioswale but towards the plot. This is done because otherwise residents have to step over the open gutter when they want to reach the backpath.	In this street stormwater from roofs is transported above ground towards a large central bioswale. In this situation it can be seen that a lamppost is placed in the middle of an open gutter. As a result of this, stormwater is not flowing in one line towards the bioswale.
Conveyance	Conveyance	Conveyance	Conveyance
Public (Municipality Roads)	Private (Residents)	Private (Residents)	Public (Municipality Roads)
Newly developed area (Vinex)	Newly developed area (Vinex)	Newly developed area (Vinex)	Newly developed area (Vinex)
Water nuisance	Water damage	Water damage	Water nuisance
Boundary plot to street	Boundary house to plot	Boundary house to plot	Street
Discomfort	Material impact	Material impact	Discomfort
Local sagging	Local sagging	Outlet not fitted correctly	Interference of obstacle
Construction phase	User/maintenance phase	Construction phase	Design phase
Lack of experience in constructing SUDS	Unclarity about maintenance responsibilities for SUDS	Fitting SUDS to unforeseen circumstances	Unfamiliarity of integrating SUDS in spatial design
Incomplete knowledge about the interactions of SUDS with urban systems			Lack of experience in constructing SUDS
			

Figure D.2: *Cases 4-7*

F.8	F.9	F.10	F.11
At this location the stormwater from the roof is above-ground drained via an open gutter towards an porous pavement street. In this situation it can be seen that the residents placed a large flowerpot directly on the open gutter.	The overflow emergency outlet of the Meerhoven water body was constructed with culverts designed for a T = 2year storm, as normal stormwater drainage pipes. This design practice is embedded in the design of stormwater drainage pipes.	In this street stormwater from roofs is transported above ground towards a central bioswale infront of the houses. In this situation it can be seen that the downspout is connected too close to the house, causing stormwater to reach the ventilation grid of the house. Because of this, water is can enter the house via the ventilation grid.	In this street stormwater flows above-ground towards bioswales infront of the houses. At the boundary zone between the plot and the street it can be seen that tiles have subsided. This is due to the electrical box that is constructed on the street. Water can flow in the gap between the tiles and the box, and washes away the underlying sand.
Conveyance	Conveyance	Conveyance	Conveyance
Private (Residents)	Public (Municipality Water)	Private (Residents)	Public (Municipality Roads)
Newly developed area (Vinex)	Newly developed area (Vinex)	Newly developed area (Vinex)	Newly developed area (Vinex)
Water nuisance	Water nuisance	Water damage	Water nuisance
Plot	Open space	Boundary house to plot	Boundary plot to street
Discomfort	Discomfort	Material impact	Discomfort
Interference of obstacle	Underdimensioned design	Outlet not fitted correctly	Local sagging
User/maintenance phase	Design phase	Design phase	User/maintenance phase
Unintended actual use of SUDS by humans	Embedded practices of the urban sector	Incomplete knowledge about the interactions of SUDS with urban systems	Incomplete knowledge about the interactions of SUDS with urban systems
		Unfamiliarity of integrating SUDS in spatial design	Lack of knowledge how to maintain SUDS
			

Figure D.3: *Cases 8-11*

F.12	F.13	F.14	F.15
At the boundary zone between the plot and the street is a pipe outlet visible. In this neighborhood stormwater is transported above ground towards a central bioswale. In this situation it can be seen that the stormwater falling at the back of the house is transported under ground towards the front of the house. As the water has to flow 'up' at the end, stagnant water remains present in the underground pipe.	The stormwater is transported above-ground via an open concrete gutter. It can be seen that at theboundary zone between the plot and the street, an obstruction is blocking the waterway.	Stormwater from houses and streets is transported towards a central bioswale. It can be seen that parking spots are constructed next to the bioswale. Raised edges have been laid to separate the parking facilities and the public space. As a result, the water can no longer run over the surface to the swale, but is transported to a gutter.	In this situation, stormwater is transported to the backpath. Because of the incorrect gradient of the surface, stormwater flows back in the direction of the house. Resulting in water nuisance in the shed.
Conveyance	Conveyance	Conveyance	Conveyance
Private (Residents)	Private (Residents)	Public (Municipality Roads)	Private (Residents)
Newly developed area (Vinex)	Newly developed area (Vinex)	Newly developed area (Vinex)	Newly developed area (Vinex)
Water pollution	Water nuisance	Minimal functionality of system	Water damage
Boundary plot to street	Boundary plot to street	Boundary street to open space	Boundary plot to street
Health impact	Discomfort	No direct impact	Material impact
Pollution	Interference of obstacle	Interference of obstacle	Insufficient slope
Construction phase	Design phase	Construction phase	Construction phase
Fitting SUDS to unforeseen circumstances	Unfamiliarity of integrating SUDS in spatial design	Embedded practices of the urban sector	Embedded practices of the urban sector
	Lack of experience in constructing SUDS	Poor communication between different actors	
			

Figure D.4: *Cases 12-15*

F.16	F.17	F.18	F.19
The urban planner decided to raise the sides of the neighborhood by 30 cm to create an eye catching view. In the neighborhood with above-ground drainage, such height differences are disastrous and therefore caused problems with the above ground drainage.	The stormwater falling on this street is above-ground drained by an open gutter towards the surface water body. In this situation it can be seen that the open gutter structure is not connected to the surface water body. Therefore, the stormwater flowing in the open gutter structure has no outlet point.	The outlet of the downspout is constructed too close to the house, creating moisture spots on the house. Furthermore, the design of the outlet point vertically transports the stormwater on the ground, instead transporting the water under a certain angle.	The greenery is separated from the cycle path by a raised curb. This makes the transport of water from the cycle path to the green no longer possible.
Conveyance	Conveyance	Conveyance	Conveyance
Private (Residents)	Public (Municipality Roads)	Private (Residents)	Public (Municipality Roads)
Newly developed area (Vinex)	Newly developed area (Vinex)	Newly developed area (Vinex)	Newly developed area (Vinex)
Water nuisance	Water nuisance	Water nuisance	Minimal functionality of system
Neighborhood	Boundary street to open space	Boundary house to plot	Boundary street to open space
Discomfort	Discomfort	Discomfort	No direct impact
Insufficient slope	Incomplete design	Outlet not fitted correctly	Interference of obstacle
Design phase	Construction phase	Design phase	Design phase
Poor communication between different actors	Lack of experience in constructing SUDS	Lack of experience in constructing SUDS	Embedded practices of the urban sector
NO PICTURE AVAILABLE			

Figure D.5: *Cases 16-19*

F.20	F.21	F.22	F.23
The municipality included in their policy that greenery should be constructed at the same level as the street, so that water from the street can flow into the greenery in case of an rainfall event. Although this is specifically stated in the design drawings, contractors tend often still construct raised curbs.	In this street, downspouts are disconnected to enable above ground drainage. It can be seen that tiles tend to subside and green rashes grow. Moreover, organic material from roofs is remains present on the surface. All these impediments can lead to discomfort by passers-by.	The stormwater from this street is drained towards a large bioswale downstream of the street. In order for the water to reach the bioswale, the water has to move first vertically and than horizontally towards the swale. It can be seen the gradient of the horizontal part is not well constructed. Therefore the water stagnates downstream of the vertical part, resulting in a large puddle in case of rainfall.	In front of these houses, a central bioswale is located. It can be seen that the roof of the houses is directed backwards, away from the bioswale. The design of the roof is not adapted to the design of the water system.
Conveyance	Conveyance	Conveyance	Conveyance
Public (Municipality Roads)	Public (Municipality Roads)	Public (Municipality Roads)	Public (Municipality Roads)
Retrofitted area (Cauliflower)	Retrofitted area (Working-class)	Retrofitted area (Low-rise garden)	Newly developed area (Vinex)
Minimal functionality of system	Water nuisance	Water nuisance	Minimal functionality of system
Boundary street to open space	Boundary plot to street	Street	Roof
No direct impact	Discomfort	Discomfort	No direct impact
Interference of obstacle	Local sagging	Insufficient slope	Unfavorable roof design
Construction phase	Design phase	Design phase	Design phase
Embedded practices of the urban sector	Incomplete knowledge about the interactions of SUDS with urban systems	Incomplete knowledge about the interactions of SUDS with urban systems	Poor communication between different actors

Figure D.6: *Cases 20-23*

F.24	F.25	F.26	F.27
For this neighboorhoud a 'construction level' was issued by the municipality. The project developer who constructed the apartment flat, constructed a storage area under the issued construction level. This storage area is lower than the rest of the area, which means that stormwater would flow into the storage area in case of heavy rainfall.	New apartments were developed in Eindhoven at the Grasbaan. The developer was only allowed to build up to a certain height, so the roof line was set at a certain NAP height. The developer lowered his building block by 1 meter under the ground level so that he could build another floor. In a neighboorhood were water is flowing above ground, the lowest places become prominant flooding locations. When the apartments were realiserd, residents have experienced flooding 1 or twice a year for multiple years. The worst of all is the psychological damage, the fact that people no longer dare to go on holidays.	In this street, the stormwater from roofs is transported to a long bioswale very close to the front door of the houses. In order for residents to reach the street, small bridges over the bioswales are constructed. When maintenance of bioswales was carried out for the first time, small stones and other things fly up and damage the houses. The maintainability was not considered in the design.	After the construction of this 'permeable pavement' it appeared that the 'normal' clay pavers were constructed instead of clay pavers with small tabs to keep clay pavers apart apart. The 'normal' clay pavers, lay too close to each other, making infiltration difficult. Therefore, the residents experience water nuisance often.
Conveyance	Conveyance	Infiltration	Infiltration
Public (Municipality Roads)	Private (Residents)	Public (Municipality Green)	Private (VVE)
Newly developed area (Vinex)	Newly developed area (Vinex)	Newly developed area (Vinex)	Retrofitted area (Working-class)
Water damage	Water damage	Causes nuisance in other domain	Water nuisance
House	House	Boundary plot to street	Street
Material impact	Material impact	Material impact	Discomfort
Wrong construction level	Wrong construction level	Low maintanability	Clogging
Design phase	Design phase	User/maintenance phase	Construction phase
Poor communication between different actors	Poor communication between different actors	Poor maintanability of SUDS	Poor communication between phases
			

Figure D.7: *Cases 24-27*

F.28	F.29	F.30	F.31
In the city center near an old monument, permeable pavement has been contructed. Due to uncertainty about the performance of the permeable pavement at that time, gullies were also contructed and the street laid under a small gradient towards the gullies. Because of that, the performance of the permeable pavement functionality is minimized.	In this municipality many streets have been renewed and constructed with permeable pavement. It appeared that the joints filling between the clay pavers disappears completely at certain locations. The water infiltration function still works well only the loose bricks cause inconvenience in other fields. The reason for this problem is not yet figured out by the municipality. In order to minimize this problem, 'miracle sand' is applied to fill the gaps between the stones.	Green facade gardens have been constructed in the city center to infiltrate stormwater that falls on the street. For practical reasons, raised edges have been constructed around the gardens. Therefore, water from the streets can no longer enter the garden. Therefore, the facade gardens has a minimal functionality.	This quare infront of an old church was retrofitted with permeable pavement of cobble stones. The church was transformed to an enormous bookstore, attracting many tourist. In the bookstore, the owner has a small cafe. He wanted to build a terras for this cafe infront of the church, but the permeable pavement contained big holes which would be inconvenient for the tables and chairs. Because of his political influnce within the municipality, the permeable pavement was removed.
Infiltration	Infiltration	Infiltration	Infiltration
Public (Municipality Roads)	Public (Municipality Roads)	Public (Municipality Green)	Public (Municipality Roads)
Retrofitted area (Downtown)	Retrofitted area (Downtown)	Retrofitted area (Downtown)	Retrofitted area (Downtown)
Minimal functionality of system	Causes nuisance in other domain	Minimal functionality of system	Causes nuisance in other domain
Street	Street	Street	Open space
No direct impact	Discomfort	No direct impact	No direct impact
Incomplete design	Poor split binding	Interference of obstacle	Decreased walkability
Design phase	User/maintenance phase	Design phase	User/maintenance phase
Undermine the functionality of SUDS by additional solution	Incomplete knowledge about the interactions of SUDS with urban systems	Embedded practices of the urban sector	Unintended actual use of SUDS by humans
			

Figure D.8: *Cases 28-31*

F.32	F.33	F.34	F.35
In this situation porous pavement is constructed at parking spots. When vegatation is constructed next to the porous pavement, the porous pavement often gets clogged by vegetational remains. Maintenance should take place regurlarly in this situation. However, operators are not used to these new maintenance requirements.	In this street gullys have been replaced by strips with permeable pavement on each side the street. The idea was to infiltrate the stormwater instead of transporting the water via the stormwater drainage system. Unfortunately, the system does not function as expected. After moderate rainfall events, water remains present on the street for minimal 1 hour. It is expected that the slow infiltration can be caused by the connection between the split and the granulate layer. To improve the infiltration, drainbreaks were installed for venting, which slightly accelerated the infiltration rate. Still the	In this area all the stormwater is transported to underground infiltration crates. In the technical PvE (made by the municipality) nothing was specifically mentioned about what type of surface material should be used. Therefor the constructor could choose what to do, and made the decision to construct gullys instead of permeable pavement.	In this area all the stormwater is transported to underground infiltration crates. In the technical PvE (made by the municipality) nothing was specifically mentioned about what type of surface material should be used. Therefor the constructor could choose what to do, and made the decision to construct gullys instead of permeable pavement.
Infiltration	Infiltration	Infiltration	Infiltration
Public (Municipality Roads)	Public (Municipality Roads)	Public (Municipality Roads)	Private (Residents)
Retrofitted area (Working-class)	Retrofitted area (Low-rise garden)	Newly developed area (Vinex)	Newly developed area (Vinex)
Water nuisance	Water nuisance	Minimal functionality of system	Minimal functionality of system
Street	Street	Street	Plot
Discomfort	Discomfort	No direct impact	No direct impact
Clogging	Clogging	Wrong construction material	Wrong construction material
User/maintenance phase	Design phase	Construction phase	Construction phase
Lack of knowledge how to maintain SUDS	Incomplete knowledge about the technical performance of SUDS	Poor communication between phases	Poor communication between phases
Poor maintanability of SUDS		Lack of experience in constructing SUDS	Lack of experience in constructing SUDS
			

Figure D.9: *Cases 32-35*

F.36	F.37	F.38	F.39
There is little surface water present in this neighborhood. To increase the storage capacity, the municipality implemented two storage systems as pilot project. Below the first half of the street crates were placed and below the other half of the street Argex material (particles that can fill up water) was placed. On top, permeable pavement was laid, to make infiltration possible. Some problems arised in the user phase. Firstly, in the user phase the maintenance department had difficulties in maintaining these types of constructions. In addition, the joint filling between the stones disappeared.	There is little surface water present in this neighborhood. To increase the storage capacity, the municipality implemented two storage systems as pilot project. Below the first half of the street crates were placed and below the other half of the street Argex material (particles that can fill up water) was placed. On top, permeable pavement was laid, to make infiltration possible. Some problems arised in the user phase. Firstly, in the user phase the maintenance department had difficulties in maintaining these types of constructions. In addition, the joint filling between the stones disappeared.	In this municipality two pilot projects were implemented. In the first pilot green parking spaces were constructed. This allowed stormwater to infiltrate into the subsurface. In the user phase of this project, problems occured. The greenery was very difficult to maintain because many cars drove over it, women with heels crushed the grass and mud was formed. Due to the poor maintanability, the pilot project was stopped.	In this municipality two pilot projects were implemented. In the second pilot a street was retrofitted with permeable pavement. A kind of gravel was used which scattered enormously in the summer months. This caused a thick yellow/white layer on the cars. This pilot project also was stopped.
Infiltration	Infiltration	Infiltration	Infiltration
Public (Municipality Roads)	Public (Municipality Roads)	Public (Municipality Green)	Public (Municipality Roads)
Retrofitted area (Working-class)	Retrofitted area (Working-class)	Retrofitted area (Low-rise garden)	Retrofitted area (Low-rise garden)
Causes nuisance in other domain	Water nuisance	Causes nuisance in other domain	Causes nuisance in other domain
Street	Street	Street	Street
Discomfort	Discomfort	Discomfort	Material impact
Poor split binding	Clogging	Decreased walkability	Wrong construction material
User/maintenance phase	User/maintenance phase	User/maintenance phase	Design phase
Incomplete knowledge about the interactions of SUDS with urban systems	Lack of knowledge how to maintain SUDS	Unintended actual use of SUDS by humans	Incomplete knowledge about the technical performance of SUDS
		NO PICTURE AVAILABLE	NO PICTURE AVAILABLE

Figure D.10: *Cases 36-39*

F.40	F.41	F.42	F.43
Removing a strip of pavement along the facade of a building allows the rainwater from the facade to infiltrate into the ground. The plants in the facade gardens increase urban biodiversity. However, these façade gardens are shielded by an steel edge. This edge is constructed often higher than the street, making water conveyance towards the gardens impossible. This minimized the infiltration of water.	In the this situation, subsurface storage crates have been installed in combination with an bioswale. Unfortunately various problems have occurred with this system. Firstly, the crates have been partially laid below groundwater level. Secondly, there were illicit connections attached to the crates, causing dirty water from the houses ending up in the crates. Thirdly, the infiltration rate is too small due to clogging. A T = 1 year rain event could be processed very tightly. Therefor water nuisance was present several times.	In this situation part the surface has been lowered and covered with small gravel stones to make infiltration of stormwater possible. Two types of problems occur in this system. Firstly, the infiltration capacity is very low (13 mm/h) due to high groundwaterlevels and clogging of the subsoil. Secondly, the small gravel stones spread easily, making maintenance of the surrounding area more difficult.	In this situation part the surface has been lowered and covered with small gravel stones to make infiltration of stormwater possible. Two types of problems occur in this system. Firstly, the infiltration capacity is very low (13 mm/h) due to high groundwaterlevels and clogging of the subsoil. Secondly, the small gravel stones spread easily, making maintenance of the surrounding area more difficult.
Infiltration	Infiltration	Infiltration	Infiltration
Private (Residents)	Public (Municipality Water)	Public (Municipality Roads)	Public (Municipality Roads)
Retrofitted area (Downtown)	Retrofitted area (Working-class)	Retrofitted area (Urban)	Retrofitted area (Urban)
Minimal functionality of system	Minimal functionality of system	Causes nuisance in other domain	Water nuisance
Boundary house to street	Open space	Open space	Open space
No direct impact	No direct impact	Discomfort	Discomfort
Interference of obstacle	Clogging	Wrong construction material	Clogging
Design phase	Design phase	Design phase	User/maintenance phase
Embedded practices of the urban sector	Incomplete knowledge about the technical performance of SUDS	Incomplete knowledge about the technical performance of SUDS	Poor maintanability of SUDS
			

Figure D.11: *Cases 40-43*

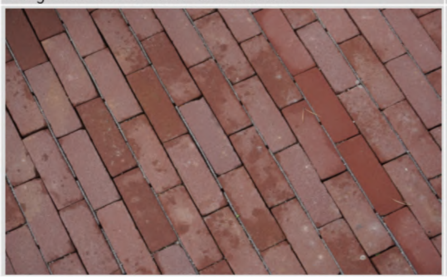
F.44	F.45	F.46	F.47
In this street a pilot project has been initiated. The street profile is constructed with a strip of water-permeable pavement (Granudrain) in the middle of the road. The idea was that all the stormwater would flow into the infiltration strip and would infiltrate. Unfortunately, many problems have occured in this system. A T=2 year rain event can not be processed because the infiltration capacity is only 10 mm/hour. Secondly, all the organic material flows to the infiltration system, which causes blockages and clogging in the system. Emergency gullies are installed..	In this street a pilot project has been initiated. The street profile is constructed with a strip of water-permeable pavement (Granudrain) in the middle of the road. The idea was that all the stormwater would flow into the infiltration strip and would infiltrate. Unfortunately, many problems have occured in this system. A T=2 year rain event can not be processed because the infiltration capacity is only 10 mm/hour. Secondly, all the organic material flows to the infiltration system, which causes blockages and clogging in the system. Emergency gullies are installed..	Infront of the station, a square with permeable pavement and drainage joints from DrainVast has been constructed. Although the drain joints between the stones should ensure that no clogging occurs, this still happened. The reason for this failure was that the stones were 9.5 centimeters and the joints 8 centimeters. Because the joints were just a bit shorter, there was a small space were organic material accumulated. This resulted in clogging of the voids between the bricks, which lowered the infiltration capacity.	In this case the stormwater from roofs and gardens (from apartments) is collected and transported towards a lowered green area. The problem is that nobody is maintaining these areas.
Infiltration	Infiltration	Infiltration	Infiltration
Public (Municipality Roads)	Public (Municipality Roads)	Public (Municipality Roads)	Public (Municipality Roads)
Retrofitted area (Urban)	Retrofitted area (Urban)	Newly developed area (Renewed)	Newly developed area (Renewed)
Water nuisance	Water nuisance	Water nuisance	Causes nuisance in other domain
Street	Street	Open space	Boundary plot to street
Discomfort	Discomfort	Discomfort	Discomfort
Clogging	Clogging	Clogging	Wrong construction material
Design phase	User/maintenance phase	Construction phase	User/maintenance phase
Incomplete knowledge about the technical performance of SUDS	Poor maintanability of SUDS	Poor communication between phases	Unclarity about maintenance responsibilities for SUDS
	Lack of knowledge how to maintain SUDS	Fitting SUDS to unforeseen circumstances	Poor communication between phases
			

Figure D.12: *Cases 44-47*

F.48	F.49	F.50	F.51
In this situation a central bioswale has been constructed for three surrounding streets. It can be seen that the vegetation on the bioswale is at some point gone, only a sand layer remains. This can occur due to a lack of maintenance. The kids who play in the bioswale are playing in this sand, which could be harmful for their health.	This central bioswale is the stromwater infiltration location for all houses and streets surrounding it. The overflow system is an concrete tank in the ground with a steel grid above it. This grid is only fastened to the concrete tank on one side. Therefore the grid can be easily lifted by people. Since the concrete container is quite large, dangerous situations could arise with children or animals. In addition, a lot of waste is collected in this concrete container.	In a newly developed part of the city, a street has been constructed with permeable pavement. After the first couple of rainfall events, it was visible that water could not drain away. The norm was set for permeable pavements that the first 90 cm of the subsoil must contain sand. Closely under this 90 cm a slib layer is present. Therefore, the water could not drain away and accumulated in the cunet. Afterwards, the permeable pavement has been re-laid and a drain installed.	For a small newly developed neighborhood, permeable pavement has been constructed by a project developer. In the permeable paved street profile several height differences are present. Because of the height differences, the stormwater is naturally flowing towards the lowest location in the street. Because no subsurface drain was constructed, water remained on the surface long after the rainfall event. Water stagnated at the lowest location in the street profile and formed puddles. This lowest location is by a coincidence exactly the location where people step out of their cars. Afterwards, a drain has been constructed to resolve these problems.
Infiltration	Infiltration	Infiltration	Infiltration
Public (Municipality Green)	Public (Municipality Water)	Private (Project developer)	Private (Project developer)
Newly developed area (Renewed)	Newly developed area (Vinex)	Retrofitted area (Working-class)	Retrofitted area (Working-class)
Creating unsafe circumstances	Creating unsafe circumstances	Water nuisance	Water nuisance
Open space	Open space	Street	Street
Health impact	Health impact	Water nuisance	Discomfort
Poor water retention capacity	Accessibility of drainage system	Unsuitable subsoil	Incomplete design
Maintenance phase	Construction phase	Design phase	Design phase
Unintended actual use of SUDS by humans	Fitting SUDS to unforeseen circumstances	Incomplete knowledge about the technical performance of SUDS	Incomplete knowledge about the technical performance of SUDS
Lack of knowledge how to maintain SUDS	Unintended actual use of SUDS by humans	Fitting SUDS to unforeseen circumstances	Lack of experience in constructing SUDS
		NO PICTURE AVAILABLE	

Figure D.13: *Cases 48-51*

F.52	F.53	F.54	F.55
A water square has been constructed with subsurface lava cases. Stormwater can infiltrate in the lava cases, whereafter the lava cases would provide a temporarily storage function. The groundlevel table beneath the water square is higher than expected, due to an unexpected water influx from the surrounding area. The square is located near the main flood defense, which is located next to a higher-lying area. The result is a high groundwater level in the section between the water square and the main flood defense, groundwater comes from the higher part to the lower part (the water square) .Therefore, the water inside the lava crates can not fully infiltrate into the subsoil. The solution is found in pumping out the water of the crates every now and then.	For water purification purposes, an infiltration construction with subsurface storage crates has been constructed under a square. The conventional stormwater system of the surrounding area is connected to this square. In the crate system an overflow has been constructed at the top of the crates. This means that the stormwater system has a high threshold. The groundwater level in the surrounding area has increased since the construction of the storage crates.	Under a large city square with a church, lava cases have been constructed. Two large pipes are constructed to transport the stormwater falling on the church towards the lava cases. The subsurface storage crates were designed with a overflow point at the highest location in the subsurface storage crates, causing the pressure to build up in the cases, enabling infiltration towards the subsoil. During construction, an extra overflow system has been constructed by constructors at the lowest point in the lava cases, causing a minimalisation of the storage and infiltration function. However, no water nuisance or direct problems are experienced.	A vegetated swale has been constructed in an Retrofitted area. During the construction of the swale, a gardener of the project developer mentioned that in order to grow plants, 80 cm of humus needs to be present in the bioswale. Instead of sand with a minimal fine fraction, humus has been applied. As a results, the water could not infiltrate well and remained present in the bioswale. To resolve this problem, a few gravel posts have been constructed. Because a drain already was constructed underneath the bioswale, the water could infiltrate in the sand layer.
Infiltration	Infiltration	Infiltration	Infiltration
Public (Municipality)	Public (Municipality Water)	Public (Municipality Water)	Public (Municipality Green)
Retrofitted area (Cauliflower)	Retrofitted area (Working-class)	Retrofitted area (Downtown)	Retrofitted area (Low-rise garden)
Water nuisance	Water nuisance	Minimal functionality of system	Water nuisance
Open space	Open space	Open space	Open space
Discomfort	Discomfort	No direct impact	Discomfort
High groundwater level	High groundwater level	Outlet not fitted correctly	Wrong construction material
Design phase	Design phase	Construction phase	Construction phase
Fitting SUDS to unforeseen circumstances	Incomplete knowledge about the interactions of SUDS with urban systems	Poor communication between different actors	Poor communication between phases
Incomplete knowledge about the technical performance of SUDS	Unfamiliarity of integrating SUDS in spatial design	Lack of experience in constructing SUDS	Lack of experience in constructing SUDS
			

Figure D.14: *Cases 52-55*

F.56	F.57	F.58	F.59
A bioswale has been constructed in order for a high-rise residential building to disconnects its stromwater to. After the construction of the bioswale, the conventional stormwater pipes had to be retrofitted so that they would lead to the bioswale instead of the underground structure. This was more difficult than expected, because of the presence of indoor stormwater pipes. Moreover, this was the domain of the private property. The process slowed down and nobody felt responsible to further take up this issue. As a result, the bioswale is constructed but the stormwater is still transported via the conventional stormwater system.	The 'living by the water' concept has been applied in this neighborhood. These houses have been designed and constructed by residents themselves. In this situation, one of the private houses has been constructed with a only a small height difference to the water. In cases of extreme rainfall, the surface water will rise and could cause flooding of this house. It can be seen that residents are not always aware of these watermanagement issues when constructing houses.	As part of the 'living by water' concept, residents were free to design and construct their own backyard and thereby the connection to the water. Traditionally, waterways are constructed with sloping sides to make maintenance of the water way possible. However residents have created 2 meter return walls to enlarge their land.	In order to create water storage, an artificial water system with large height differences has been constructed. From the lowest part of the plan, water is pumped up through a pumping station, it then falls via a waterfall to the middle level and continues its way via a naturally designed route to the low level. This artificial water system was designed with the idea that the pump is always running. Because water is flowing, a storage supporting disc of 10 centimeter is created in the system. When the pump is switched off, the water sinks in different places, resulting in one single water level. At that moment, as the overflow was located at the lowest point in the water system, the overflow discharges its water. Causing almost no water left in the system.
Infiltration	Storage	Storage	Storage
Private (VVE)	Private (Residents)	Private (Residents)	Water board
Retrofitted area (High-rise)	Newly developed area (Vinex)	Newly developed area (Vinex)	Newly developed area (Vinex)
Minimal functionality of system	Water nuisance	Minimal functionality of system	Minimal functionality of system
Open space	Boundary house to water body	Boundary house to water body	Transtion area open space to water body
No direct impact	Material impact	No direct impact	Discomfort
Incomplete design	Wrong construction level	Low maintanability	Incomplete design
Construction phase	Design phase	Design phase	Design phase
Poor communication between different actors	Poor communication between different actors	Poor maintanability of SUDS	Incomplete knowledge about the interactions of SUDS with urban systems
			

Figure D.15: *Cases 56-59*

F.60	F.61	F.62	F.63
The water storage for the newly constructed houses of this neighborhood is located slightly higher than its surroundings. This water storage pond has been combined with houses on the water. The architect stated that to live by the water, the distance between the living area and the water should not be more than 15 centimeters. Because of this decision, the water storage capacity was decreased from 50 centimeters to barely 15 centimeters. Therefor the original storage function of the water boday was no longer sufficient. In order to solve this problem, a small that serves as emergency overflow was created.	In this new neighboorhood a shopping center has been built, with a deepened parking garage below. Directly next to the parking garage, surface water is located. The retaining wall of this parking garage has become a very determining factor for the final design of the complete water system of this newly build neighborhood. The height of the retaining wall is the only factor that minimizes the storage ability of this water. If the wall had been made 20 cm higher, there would have been 20 cm more storage in the system. The whole system needs to be addapted to height of this wall.	The idea in this situation was that that the electricity mast would already be removed before the construction of the houses. Therefore, the design of the houses was not adjusted to the electricity mast. When the design of the houses was already finished, it became clear that the electricity was not removed yet.	In this situation, crates were installed in combination with an bioswale. Unfortunately various problems arose. Firstly, the crates were partially laid out below groundwater level. Secondly, there were illicit connections attached to the crates, causing dirty water from the houses ending up in the crates. .
Storage	Storage	Storage	Infiltration
Water board	Water board	Water board	Public (Municipality Water)
Newly developed area (Vinex)	Newly developed area (Vinex)	Newly developed area (Vinex)	Newly developed area (Renewed)
Minimal functionality of system	Minimal functionality of system	Causes nuisance in other domain	Water nuisance
Boundary house to water body	Boundary house to water body	Transtion area open space to water body	Open space
No direct impact	No direct impact	No direct impact	Discomfort
Limited freeboard	Limited freeboard	Interference of obstacle	High groundwater level
Design phase	Design phase	Construction phase	Design phase
Poor communication between different actors	Poor communication between different actors	Fitting SUDS to unforeseen circumstances	Incomplete knowledge about the technical performance of SUDS
			

Figure D.16: *Cases 60-63*

F.64	F.65	F.66	F.67
In the this situation, subsurface storage crates have been installed in combination with an bioswale. Unfortunately various problems have occurred with this system. Firstly, the crates have been partially laid below groundwater level. Secondly, there were illicit connections attached to the crates, causing dirty water from the houses ending up in the crates. Thirdly, the infiltration rate is too small due to clogging. A T = 1 year rain event could be processed very tightly. Therefor water nuisance was present several times.	A water square has been constructed with subsurface lava cases. Stormwater can infiltrate in the lava cases, whereafter the lava cases would provide a temporarily storage function. The groundlevel table beneath the water square is higher than expected, due to an unexpected water influx from the surrounding area. The square is located near the main flood defense, which is located next to a higher-lying area. The result is a high groundwater level in the section between the water square and the main flood defense, groundwater comes from the higher part to the lower part (the water square) .Therefore, the water inside the lava crates can not fully infiltrate into the subsoil. The solution is found in pumping out the water of the crates every now and then.	For water purification purposes, an infiltration construction with subsurface storage crates has been constructed under a square. The conventional stormwater system of the surrounding area is connected to this square. In the crate system an overflow has been constructed at the top of the crates. This means that the stormwater system has a high threshold. The groundwater level in the surrounding area has increased since the construction of the storage crates.	Under a large city square with a church, lava cases have been constructed. Two large pipes are constructed to transport the stormwater falling on the church towards the lava cases. The subsurface storage crates were designed with a overflow point at the highest location in the subsurface storage crates, causing the pressure to build up in the cases, enabling infiltration towards the subsoil. During construction, an extra overflow system has been constructed by constructors at the lowest point in the lava cases, causing a minimalisation of the storage and infiltration function. However, no water nuisance or direct problems are experienced.
Infiltration	Infiltration	Infiltration	Infiltration
Public (Municipality Water)	Public (Municipality)	Public (Municipality Water)	Public (Municipality Water)
Newly developed area (Renewed)	Retrofitted area (Cauliflower)	Retrofitted area (Working-class)	Retrofitted area (Downtown)
Water pollution	Water nuisance	Water nuisance	Minimal functionality of system
Open space	Open space	Open space	Open space
Economic impacts	Discomfort	Discomfort	Discomfort
Illicit connections	High groundwater level	High groundwater level	Outlet not fitted correctly
Construction phase	Design phase	Design phase	Construction phase
Lack of experience in constructing SUDS	Fitting SUDS to unforeseen circumstances	Incomplete knowledge about the interactions of SUDS with urban systems	Poor communication between different actors
	Incomplete knowledge about the technical performance of SUDS	Unfamiliarity of integrating SUDS in spatial design	Lack of experience in constructing SUDS




Figure D.17: *Cases 64-67*

F.68	F.69	F.70
There is little surface water present in this neighborhood. To increase the storage capacity, the municipality implemented two storage systems as pilot project. Below the first half of the street crates were placed and below the other half of the street Argex material (particles that can fill up water) was placed. On top, permeable pavement was laid, to make infiltration possible. Some problems arised in the user phase. Firstly, in the user phase the maintenance department had difficulties in maintaining these types of constructions. In addition, the joint filling between the stones disappeared.	In this situation part the surface has been lowered and covered with small gravel stones to make infiltration of stormwater possible. Two types of problems occur in this system. Firstly, the infiltration capacity is very low (13 mm/h) due to high groundwaterlevels and clogging of the subsoil. Secondly, the small gravel stones spread easily, making maintenance of the surrounding area more difficult.	Bioswales are constructed infront of these houses. In order to get from the house to the streets, a small bridge has been placed. The bridge is located only a couple centimters above the swale surface. This minimizes the storage capacity of th swales.
Storage	Storage	Storage
Public (Municipality Roads)	Public (Municipality Roads)	Public (Municipality Green)
Retrofitted area (Working-class)	Retrofitted area (Urban)	Newly developed area (Vinex)
Causes nuisance in other domain	Minimal functionality of system	Minimal functionality of system
Street	Open space	Street
Discomfort	Discomfort	No direct impact
Clogging	High groundwater level	Interference of obstacle
User/maintenance phase	Design phase	Design phase
Lack of knowledge how to maintain SUDS	Incomplete knowledge about the technical performance of SUDS	Incomplete knowledge about the interactions of SUDS with urban systems



Figure D.18: *Cases 68-70*

Appendix E

Results root cause analysis

The root analysis consisted of three steps. The first and second step are presented below.

Table E.1: *Root causes definition of step 1*

	Root causes (step 1)
1	Transfer from 3D to 2D design
2	Lack of standards for novel UD solutions
3	The traditional way of separating traffic from greenery and water bodies
4	The traditional design of the public spaces in the Netherlands
5	The unfamiliarity of integrating SUDS in spatial design
6	The norm-oriented mindset in the Netherlands
7	Aesthetic considerations in design
8	Adaptation of system to temporary 'construction' situation
9	Unforeseen changes in construction phase
10	Lack of experience of constructors on SUDS
11	Lack of supervision from municipality during construction
12	Hiring external agencies for supervision practices
13	Traditionally constructing green with raised sites
14	Traditionally constructing on 1 height level
15	Traditionally constructing curb lower than street
16	The fased construction of plots
17	Unfamiliarity of responsible maintenance party
18	Unfamiliarity of residents about the responsibility for maintenance
19	Lack of maintenance standards of SUDS
20	Lack of maintenance
21	Maintenance budgets not adapted to SUDS maintenance
22	The degree of maintainability not included in the design
23	Uncertainty about the SUDS functionality
24	Insufficient confidence in SUDS
25	Unfamiliarity about the social impacts of the SUDS
26	Unforeseen side effects of SUDS
27	Lack of knowledge about the performance of SUDS in practice
28	Lack of knowledge of long term performance SUDS
29	Lack of social understanding about the role of SUDS
30	Poor communication between actors
31	Uneven level of knowledge among actors
32	Unfamiliarity of residents about the function of SUDS
33	Lack of information about the subsoil conditions (only point information)
34	Lack of knowledge about the impact on the groundwater characteristics
35	Lack of experienced staff
36	Lack of monitoring and evaluating the performance of SUDS

Table E.2: *Root causes definition step 2*

	Root causes (Step 2)
1	Traditional design of the public space in the Netherlands
2	Unfamiliarity of integrating SUDS in spatial design
3	Lack of knowledge about the interaction of SUDS with other urban systems
4	Lack of knowledge about interaction of SUDS with the subsoil
5	Lack of knowledge about the social interaction of humans with SUDS
6	Norm-oriented mindset in the Netherlands
7	Maintainability not considered in design of SUDS
8	Transition from 3D to 2D design
9	Poor communication between actors
10	Uncertainty about the SUDS functionality
11	Fitting SUDS to the temporary construction situation
12	Embedded practices of constructors
13	Lack of experience how to construct SUDS
14	Unforeseen changes during construction phase
15	Unfamiliarity about the responsibility for maintenance of SUDS
16	No agreements made about the maintenance of transition zones
17	Lack of knowledge how to maintain SUDS
18	Lack of the social understanding of the role of SUDS