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Root causes of failures in sustainable urban drainage systems (SUDS): an exploratory study in 11 municipalities in the Netherlands

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ABSTRACT

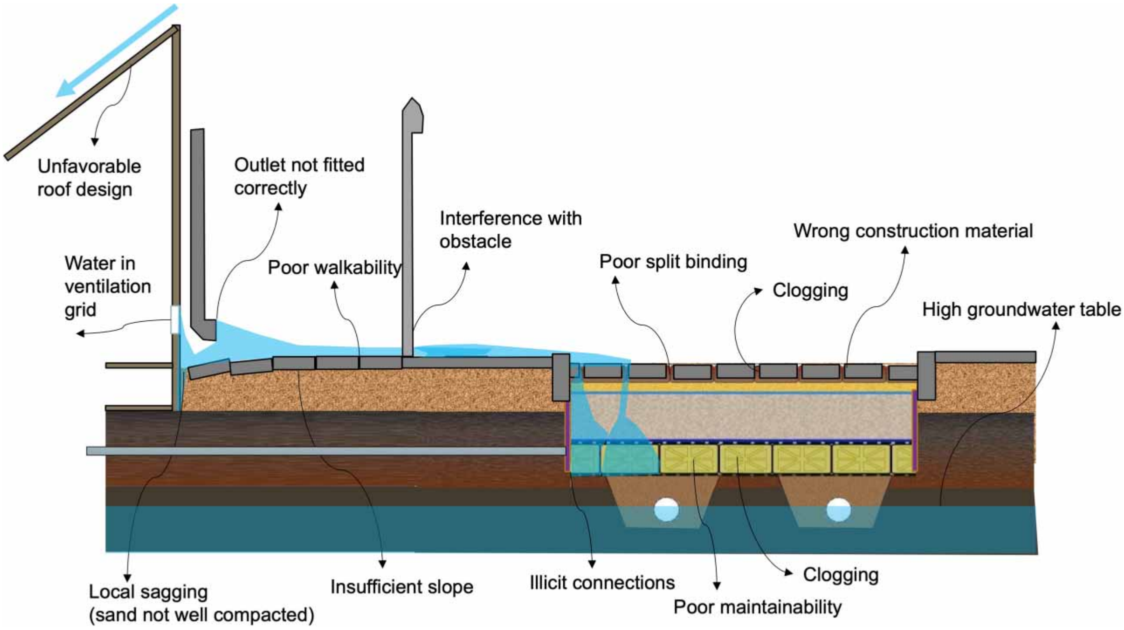
Despite being widely implemented, sustainable urban drainage systems (SUDS) do not always function flawlessly. While SUDS have been tested extensively and seem to perform well on a laboratory or pilot scale, practitioners' experience is different: failures in SUDS occur regularly in practice, resulting in malfunctioning systems, water nuisance and high costs. To anticipate their malfunctioning, and thus to improve their performance, a better understanding of failures occurring in SUDS and their underlying causes is needed. Based on an explorative case-study approach, consisting of site visits and semi-structured interviews with urban water professionals, this study presents an inventory of technical failures in SUDS and an analysis of their root causes. In total, 70 cases in 11 Dutch municipalities have been documented. The results show that the interfaces between SUDS and other urban systems are prominent failure locations. In addition, we found that failures originate from the entire development process of SUDS, i.e., from the design, construction and user/maintenance phase. With respect to the causes underlying these failures, our results show that these are mainly socio-institutional in nature. These are valuable insights for both practitioners and scholars, contributing to a renewed socio-technical urban water system with more sustainable water management practices.

Key words: blue-green systems (BGS), failures, malfunctioning, root causes, storm water management, sustainable urban drainage systems (SUDS)

HIGHLIGHTS

- This study analyzes the malfunctioning of SUDS in practice and identifies the causes underlying this malfunctioning.
- We found that interfaces between SUDS and other urban systems are prominent failure locations.
- The causes underlying these failures were mainly socio-institutional, rather than technical in nature.
- Practitioners need to acquire new knowledge and develop their skills for the successful management of SUDS.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Traditionally, urban water management has focused on providing safe, reliable, and cost-effective water services. The protection of public health was at the heart of the development of sewer systems, and their construction has been a key development to modern city life. Together with centralized water supply, and large-scale water treatment facilities, sewer systems have become the dominant urban water system (Wong & Brown 2009). Growing societal attention to pollution control and environmental protection, however, has led to the questioning of the effectiveness of traditional sewer systems (Chocat *et al.* 2007). In response to these environmental concerns, a push towards more integrated storm water solutions has emerged in the past decades (Qiao *et al.* 2018). This shift to novel integrated storm water solutions has received growing attention all over the world and has led to the parallel development of new storm water concepts. Examples include sustainable urban drainage systems (SUDS), low impact development (LID) (Fletcher *et al.* 2015), and a more recent one, sponge cities (Jiang *et al.* 2018). These concepts are often used interchangeably, and sometimes together referred to as blue-green systems (BGS) (Deletic *et al.* 2020). Throughout this paper, we use the term SUDS, which can be broadly defined as technologies and techniques used to manage storm water and surface water in a manner that is more sustainable than conventional solutions (Fletcher *et al.* 2015). These SUDS use principles such as infiltration and storage, thereby not only processing water, but also contributing to the urban environment in an environmental, as well as a social and economic sense (Zhou 2014; Cohen-Shacham *et al.* 2016).

Over the past three decades, SUDS have been widely implemented in both newly developed and existing urban areas. They have become a viable alternative to the traditional sewer infrastructure. This does not imply, however, that SUDS always function appropriately (Marlow *et al.* 2013). We see at least three issues attributing to the malfunctioning of SUDS:

- First of all, SUDS make use of different technologies than conventional solutions and thus also require different knowledge and skills for their implementation, their operation and maintenance (Brown & Farrelly 2009). This shift to new technologies, to which practitioners are not yet familiar, potentially increases the risk of failure.
- Second, SUDS inevitably require crossing of conventional system boundaries, and there is only limited knowledge of what is happening at the interfaces between the previously unconnected systems (Veeneman 2004). Unlike sewer pipes, SUDS are often located above the ground, extending to both public and private spaces such as streets, parks and gardens. SUDS, therefore, set different requirements for other urban systems, which have not been designed for drainage functions previously (Hoang & Fenner 2016). While the domains in charge of each of the other urban systems have much knowledge about their own system, there is only limited

knowledge of what is happening at the interfaces between these systems, increasing the risk of failure (Nieuwenhuis *et al.* 2021).

- Lastly, the relational complexity introduced with SUDS adds to the likelihood of its malfunctioning (Fratini *et al.* 2012). Compared with decision-making on conventional drainage solutions, decision-making on SUDS inevitably involves actors from multiple disciplines (Hoang & Fenner 2016; Cotterill & Bracken 2020). These actors all have their own responsibilities and interests, as well as their system logics. This makes decision-making less straightforward, complicates communication, and fosters misunderstandings.

These issues illustrate that the malfunctioning of SUDS is not only a technical issue, but also relates to socio-institutional aspects: the different actors involved and the institutions that direct the perceptions and actions of these actors. How do these observations relate the urban water literature? So far, the malfunctioning and performance of SUDS has mainly been described in technical studies, often on a laboratory or pilot scale (Scholz & Grabowiecki 2007; Geiger *et al.* 2010; Xie *et al.* 2019), or in clearly defined experimental settings. In addition, much of the available research focused on only a few issues, such as hydraulic performance (Chu & Fwa 2019) or clogging of infiltration facilities (Abbott & Comino-Mateos 2001; Scholz & Grabowiecki 2007; Boogaard *et al.* 2014). A few studies looked at the social–technical interactions between SUDS and the wider urban landscape (e.g., Fratini *et al.* 2012; Hoang & Fenner 2016); however, these did not investigate the malfunctioning of SUDS in practice. Research on the overall performance of SUDS is thus scarce (Cotterill & Bracken 2020).

Besides, while the management of SUDS has received little attention in the literature, sewer asset management, i.e., the maintenance and rehabilitation of sewer infrastructure to prevent malfunctioning, has received extensive attention (see Tscheikner-Gratl *et al.* 2019 for an overview). In addition, asset management practices are deeply embedded in institutions, with legal frameworks and guidelines that prescribe how to manage and operate sewers (see, e.g., the standards NEN-EN 752:2017 (2017) and NEN-EN 13508-2:2003 + A1:2011 nl (2020)). Since the 1980s, there has been a shift away from constructing new sewer infrastructure, toward the rehabilitation and maintenance of existing systems (Oomens 1992). A similar shift is required for SUDS now, i.e., toward the management of SUDS.

Practitioners need to acquire new knowledge and develop their skills for the successful management of SUDS. The traditional socio-technical urban water system, comprising the infrastructure and all organizations and people directly and indirectly (researchers, education etc.) involved in operation and maintenance, has evolved over decades. This has resulted in well-described and defined procedures. However, the socio-technical system has changed because of the implementation of SUDS (Cotterill & Bracken 2020). SUDS have different design, operation, and maintenance requirements, and thus also need a different management approach. To foster the learning of practitioners, and to anticipate the malfunctioning of SUDS, it is crucial to better understand the failures that occur in SUDS, as well as their underlying causes.

This paper works toward a better understanding of failures occurring in SUDS, adopting a socio-technical systems perspective. We use an exploratory case-study approach: (1) to identify technical failures of SUDS occurring in practice and (2) to explore the root causes underlying the malfunctioning of these SUDS based on interviews with professionals. These insights serve to anticipate failing systems, aiming to improve the functioning of SUDS and to add to their reliability. As such, this study has the objective to contribute to a renewed socio-technical urban water system with more sustainable water management practices.

2. METHODS

2.1. Site selection

This study investigates failures in SUDS using a case-study approach. In total, 70 cases in 11 different municipalities throughout the Netherlands were collected. Table 1 provides an overview of the municipalities and the site characteristics. Selection criteria were the presence of SUDS and the willingness of an urban water professional to participate in the research, as well as the geographical location and the type of area (greenfield or brownfield areas).

2.2. Data collection

In each municipality, we collected cases of technical failures in SUDS through site visits. Additionally, we conducted semi-structured interviews with urban water professionals who were involved in the implementation and/or operation of the SUDS.

Table 1 | Overview of the site characteristics

Municipality (neighborhood in parentheses)	Type of area	Type of SUDS	Number of failures
Eindhoven (Meerhoven)	Greenfield	Subsurface storage	4
Nijmegen (Centrum)	Green- and brownfield	Bioswales	2
Nijmegen (Waalsprong)	Greenfield	Bioswales	10
Utrecht (Leidsche Rijn)	Greenfield	Bioswales, permeable pavement	10
Almere (Homeruskwartier)	Greenfield	Bioswales, permeable pavement	7
Zwolle (Stadshagen and Centrum)	Green- and brownfield	Permeable pavement, soakaway crates	10
Gouda	Brownfield	Permeable pavement, soakaway crates	3
Tilburg	Brownfield	Facade gardens	1
Diemen	Brownfield	Above-ground storage, soakaway crates	1
Dordrecht	Brownfield	Underground storage	2
Rotterdam	Brownfield	Permeable pavements, soakaway crates, bioswales, subsurface storage	10
Amsterdam	Brownfield	Bioswales, subsurface storage, permeable pavement	10

The type of area indicates whether the SUDS were built in a greenfield area, or in a redeveloped brownfield area. In case of a greenfield area, the specific neighborhood is provided in parentheses.

The cases were collected based on what the professionals identified as malfunctioning SUDS, i.e., where the system failed to achieve its intended function according to the urban drainage professionals. Every single location where the professional indicated a failure in the SUDS constitutes a unique case. These cases were photographed, and a short description of the situation was added based on the information given by the professionals.

To maintain a clear scope in this exploratory research and to enhance consistency between the analyzed cases, we decided to interview urban drainage professionals only. The interview questions focused on three main issues: the general experiences that these professionals had with SUDS, the failures of SUDS in the specific study site(s), and their view on the underlying reason for these failures.

2.3. Data analysis

2.3.1. Failure characteristics

All failures were analyzed based on four SUDS characteristics: technical failure, failing function, failure location, and phase of failure. Table 2 provides an overview of these characteristics and their corresponding categories. During the site visits, we iteratively refined the categories. To ensure they properly describe the data set, we subsequently verified them during the interviews.

2.3.1.1. Technical failure. The categories for technical failures were primarily based on previous research. The technical failures most prevalent in the literature are the following: clogging (Abbott & Comino-Mateos 2001; Boogaard & Wentink 2007), low maintainability of SUDS (Boogaard & Rombout 2008; McDonald 2018), insufficient slope for the conveyance of water (Pötz 2016), and illicit connections in subsurface infiltration systems (Boogaard & Rombout 2008; Heppenhuis 2020). In case these categories were not able to describe the failure properly, new technical failures were added after consulting with the professionals.

2.3.1.2. Failing function, failure location, and phase of failure. The other case characteristics, which are more descriptive in nature, are documented according to the categories presented in Table 2. The categories for the case characteristic *failure location* were grouped into *internal* and *interface locations*. *Internal* refers to failures occurring within a single urban system, and *interface* refers to failures occurring at the physical interface between two systems.

Table 2 | Overview of the four case characteristics and their initial categories

Case characteristics	Description	Categories
Technical failure	The technical issue that causes malfunctioning	Clogging; poor maintainability; insufficient slope; illicit connections
Failing function	The main hydraulic function of the system	Conveyance; infiltration; storage
Failure location	The location of the failure	Internal locations: roof; house; private plot; street; public open space; water body Interface locations: between roof and house; between house and private plot; between private plot and street; between street and public open space; between public open space and surface water body
Phase of failure	The project phase where the failure originated from	Design phase; construction phase; user/maintenance phase

These categories were further refined during the site visits. The case characteristic failure location is subdivided into internal and interface locations.

2.3.2. Root causes

To find the underlying reasons for the technical failures occurring in each of the SUDS, 11 interviews with urban drainage professionals were conducted. During these interviews, one or more causes were identified for each case. To come to a comprehensible list of root cause, we subsequently removed double causes and rephrased overlapping ones. We used a socio-technical systems perspective to develop a balanced set of causes, i.e., comprising both causes with a technical nature and causes related to the behavior of actors and their institutions. When root causes had only one or two cases, we looked for a more general description of that root cause, such that it could be assigned to at least three cases, while each case could (still) be well described by one of the root causes.

2.3.3. Analysis of the technical failures and root causes

In order to explore the relationship between the technical failures and the other case characteristics, we combined data on the technical failures with those on the other case characteristics. In addition, we combined data on the causes underlying the technical failures with data on the four case characteristics of SUDS.

3. RESULTS AND DISCUSSION

In total, 70 cases of failure were identified in 11 municipalities throughout the Netherlands. The database of all cases is provided in the Supplementary Material (Database of 70 failure cases).

3.1. Technical failures

Eighteen different technical failures were identified, eight of which were mentioned earlier in literature and 10 of which followed from the empirical data (see Table 3).

3.2. Failing function

Table 4 gives an overview of the number of cases for each failing function.

The most commonly observed technical failures for each of the three functions of SUDS (infiltration, transport, or storage) are the following:

- *Infiltration*: *Clogging* (9 out of 36 cases) was identified as the most common technical failure occurring in infiltration systems. This is in line with previous research, as clogging has been frequently associated with the failing of swales, permeable pavements, and infiltration crates (Scholz & Grabowiecki 2007; Hatt *et al.* 2009; Bergman *et al.* 2011).
- *Conveyance*: The most common technical failure identified for conveyance systems was *Interference with obstacle* (7 out of 25 cases) (see Figure 1 for an example). This technical failure was previously mentioned by Boogaard *et al.* (2006). The second most common failure is *Insufficient slope* (4 out of 25 cases), which is also in line with previous studies (Boogaard *et al.* 2006; Pötz 2016).
- *Storage*: The most common technical failures of storage systems were *limited freeboard* and *interference with obstacle* (both 2 out of 9 cases). We did not find the relevant literature about these failures.

Table 3 | Overview of the number of cases for each technical failure

Technical failure	Number of cases
Interference with obstacle	11
Clogging	10
Incomplete design	8
Wrong construction material	6
High groundwater table	6
Outlet not fitted correctly	5
Insufficient slope	4
Local sagging	3
Wrong construction elevation	3
Poor maintainability	3
Limited freeboard	2
Poor walkability	2
Accessibility of drainage system	2
Poor split binding (wrong material used)	2
Pollution	1
Illicit connections	1
Unfavorable roof design	1
Total	**70**

The gray color highlights the technical failures that are based on empirical research. The other ones are found in the literature.

Table 4 | Overview of the number of cases for each failing function

Failing function	Number of cases
Infiltration	36
Conveyance	25
Storage	9
Total	**70**

Figure 1 | Two cases (#13 and #15) of technical failures in SUDS with a failing function of conveyance. Left: an obstacle interferes with the transport of water by an open gutter. Right: due to insufficient slope of the garden, the storm water flows into the shed.

3.3. Failure location

Table 5 presents an overview of the failure locations observed in the 70 cases, differentiating between *internal locations* and *interface locations*. *Internal* refers to failures occurring within a single urban system, and *interface*

Table 5 | Overview of the number of cases for each failure location

Failure location	Number of cases
Internal locations	
Public open space	21
Street	19
House	2
Private plot	1
Roof	1
Water body	0
Subtotal	**44**
Interface locations	
Between private plot and street	11
Between street and public open space	5
Between private plot and water body	4
Between house and private plot	4
Between public open space and water body	2
Subtotal	**26**
Total	**70**

refers to failures occurring at the physical interface between two systems. See Figure 2 for an illustration of the failure locations per type of SUDS.

Table 5 reveals that almost 40% of the failures occur at the physical interfaces of urban systems, i.e., where the physical infrastructures of two urban systems meet. These failures are thus not related to internal processes of SUDS, such as their hydraulic performance. Figure 2 shows that such interfaces are typically associated with physical changes in surfaces (e.g., paved surface to vegetation), height differences (e.g., a sidewalk), and structures (e.g., a fence), suggesting that these make them prone to failure. In addition, physical interfaces often mirror the boundaries of ownership and/or responsibility (e.g., private versus public ownership, or between two different public domains). Ambiguity as to who is responsible for maintenance at such interfaces could therefore be the reason for the malfunctioning of these SUDS.

The observation that interfaces play an important role in the malfunctioning of SUDS is also supported by previous research: Nieuwenhuis *et al.* (2021) looked at integrated urban water solutions and found that interfaces, which emerge at the locations where previously unconnected systems become interconnected, are an important

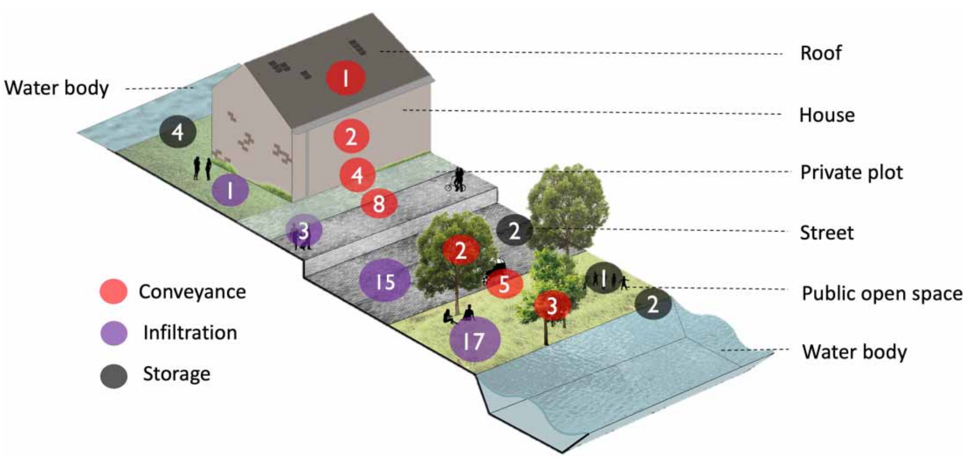


Figure 2 | Overview of the number of technical failures of SUDS that occur at different locations in the urban area. The colors indicate the hydraulic functions of the SUDS.

source of uncertainty. These make it more difficult to understand the overall system behavior and thereby increase the risk of failure. They explained that such interfaces involve many potential mismatches, which could be both technical and socio-institutional in nature – thus mismatches related to physical changes in surfaces and those related to the boundaries of responsibility and ownership, respectively.

3.4. Phase of failure

Table 6 provides an overview of the phases where the failures originate from. Fifty percent of the failures (35 cases) originated from the design phase. The construction (19 cases) and the user/maintenance phase (16 cases) together accounted for the other 50%. Hence, in each of the project phases, a significant proportion of failures finds its origin, meaning that each project phase needs attention to develop well-performing SUDS. This is supported by the research of Rijke *et al.* (2008) who concluded that all phases of the development process are important to successfully implement innovative water systems.

3.5. Root causes

This section provides an overview of the root causes identified for the technical failures occurring in the 70 SUDS. Based on the interviews with urban water professionals, an initial list of 36 causes was identified (see Supplementary Material, Appendix A). This was subsequently reduced to a final set of 11 unique root causes, based on the procedure outlined in Section 2.3.2. For 21 cases, we assigned two root causes, and for the remaining cases (49), only one cause was assigned. Table 7 shows the final list of root causes. The gray highlights indicate the most prevalent root causes, which are discussed in more detail. For the other ones, only a brief description is provided. We subsequently discuss the final set of root causes as a whole, reflecting on their nature.

3.5.1. The final eleven root causes

3.5.1.1. Root cause 1: embedded practices of involved actors. This root cause relates to the dominant and traditional thoughts, knowledge, and skills of practitioners in various urban sectors (e.g., water, green, or

Table 6 | An overview of the number of cases for each phase of failure

Phase of failure	Number of cases
Design phase	35
Construction phase	19
User/maintenance phase	16
Total	**70**

Table 7 | Overview of the final set of 11 root causes

Root causes	Number of cases
1. Embedded practices of involved actors	13
2. Poor communication between different actors	12
3. Incomplete knowledge about the interactions of SUDS with other urban systems	11
4. Incomplete knowledge about the technical performance of SUDS	11
5. Lack of experience in constructing SUDS	10
6. Fitting SUDS to unforeseen circumstances	8
7. Actual use of SUDS by humans	6
8. Poor communication between phases	6
9. Lack of knowledge how to maintain SUDS	6
10. Poor maintainability of SUDS	5
11. Ambiguity about the maintenance responsibilities	3
Total	**91**

The five root causes that are highlighted in gray are the most common root causes.

roads), leading to the incorrect design, construction, or maintenance of SUDS, and ultimately its malfunctioning. Sometimes, these embedded practices are based on guidelines, but they could also be routines. Four interviewees explained that particular ways of working or traditional measures can be so deeply embedded in practices that they are hard to change. They mentioned, for example, the construction of raised edges around green spaces (see Figure 3) and that of convex-shaped roads. Both hamper the handling of storm water above the ground and thus limit the functioning of SUDS.

Our findings are supported by the work of Roy *et al.* (2008), who found that standards and engineering guides sometimes prevent the use of SUDS in a way that their advantages are actually utilized; for example, they noticed that codes prescribe the installation of gutters and curbs alongside roads and thus also alongside those with permeable pavement. This illustrates that the urban drainage system is a socio-technical system, and that new SUDS technologies therefore also require changing the socio-institutional system. SUDS impose new demands on the people in charge of designing, constructing, and maintaining such systems, and practitioners therefore need to develop new knowledge and skills, e.g., through training. In addition, policies, guidelines, and standards need change, to make sure they support the proper design, implementation, and use of SUDS. Kiparsky *et al.* (2013) refer to this as *institutional innovation* and argues this is of similar importance to technological innovation.

In addition, the multifunctionality of SUDS implies that SUDS set different requirements for other urban systems, which have not been designed for drainage functions previously (Hoang & Fenner 2016). Beside the municipal urban drainage department, there are many other actors involved. These all work according to their own rules and practices, while influencing the performance of SUDS. Hence, not only the physical interfaces (see Section 3.3.) that emerge with the shift to SUDS should be managed, but the urban drainage sector should also deal with the socio-institutional interfaces, i.e., the other actors in the urban environment and the institutions that guide these actors.

3.5.1.2. Root cause 2: poor communication between different actors. This root cause concerns both the communication between actors belonging to a specific group, such as between actors within the municipal sewer department, and the communication between different actor groups, e.g., between two different departments at the municipality, or between the municipality and external parties such as project developers, civil engineering consultants, and/or architects.

The multifunctionality of SUDS implies that decision-making on the design, implementation, and maintenance of SUDS involves actors from different disciplines. These actors all have their own responsibilities and interests, as well as their (sector-specific) terminology. Hence, they are not always naturally aware of the water function of SUDS, neither do they have the 'urban water vocabulary'. This complicates communication, thereby increasing the risk of failure.

An example of such poor communication leading to malfunctioning SUDS is illustrated in Figure 4. The interviewee explained that architects typically want to minimize the distance between the ground-floor level of the house and the water level (in this case 0.15 m), aiming for a closer connection with the water – a so-called 'living-on-water-experience'. The municipality, however, generally designs water systems with a large freeboard

Figure 3 | Case #30: a facade garden, which has been assigned the root cause embedded practices of involved actors. A facade garden is typically constructed surrounded by raised borders. Preventing runoff to be drained into the garden, this reduces the effectiveness of the SUDS.

Figure 4 | Case #60 has been assigned the root cause poor communication between different actors. Due to lacking communication between the architect and the municipality, the houses were built only 0.15 m from the water level. This minimized the storage capacity of the surface water, while the water was initially designed as a storm water detention pond with a freeboard of 0.70 m.

(in this case 0.70 m) to increase the storage capacity of the water, which could prevent urban flooding after heavy rainfall, as well as water shortage in case of drought. These requirements, however, were not communicated clearly in the decision-making process, which eventually resulted in the houses being constructed with little freeboard. As the storage capacity now had to be realized elsewhere in the urban water system, this brought along high costs.

3.5.1.3. Root cause 3: incomplete knowledge about the interactions of SUDS with other urban systems. This root cause refers to the lack of knowledge of urban practitioners about the interactions of SUDS with other urban systems in public space. Several interviewees indicated that interactions of SUDS with other systems are hard to predict beforehand. They explained that there are many different types of SUDS, and that their functioning highly depends on local conditions. This makes it very challenging to predict the interactions that will take place at the interfaces with other urban systems.

Figure 5 presents an example of the unexpected impact of car traffic on the performance of permeable pavement. After the implementation of the pavement, it turned out that car traffic resulted in friction between the stones. This damaged the joint fillings between the bricks and eventually led to their disappearance. As the practitioners had no experience with permeable pavement yet, they did not anticipate the long-term effects of cars on this type of porous pavement construction.

Previous research pointed out that implementing SUDS in a complex urban environment results in new system interactions, and could potentially pose negative impacts on the functioning of both SUDS and other urban systems (Hoang & Fenner 2016). Such interactions emerging at the interfaces between previously unconnected systems are an important source of uncertainty: they increase the complexity, making it more difficult for decision-makers to understand the overall system behavior (Nieuwenhuis *et al.* 2021).

3.5.1.4. Root cause 4: incomplete knowledge about the technical performance of SUDS. This root cause represents the lack of knowledge about the internal processes that occur within SUDS. Four interviewees

Figure 5 | Case #29 has been assigned the root cause *Incomplete knowledge* about the interactions of SUDS with other urban systems. Due to the impact of cars as well as street sweeping, the joints of the permeable pavement bricks vanished. This decreased the overall performance of the SUDS, i.e., the stability of the road surface.

explained that this incomplete knowledge typically stems from the limited monitoring that is carried out in SUDS. They argued this prevents learning and results in unnecessary failures. In addition, one interviewee reported that in some cases, designers do not have the knowledge and/or experience to properly understand the internal processes occurring in SUDS. This relates, for example, to incomplete knowledge about the subsoil. As compared with sewers, the subsoil forms an important part of SUDS, particularly in the case of infiltration facilities. The design is then often based on the very limited information available about the subsoil, if at all. When SUDS are then constructed in practice, the subsoil sometimes has other characteristics than expected, resulting in malfunctions. For instance, the soil contains more clay, or groundwater levels are higher than expected, decreasing the permeability of the soil, or reducing the subsurface storage capacity, respectively. An example is provided in Figure 6.

These findings are supported by the empirical study on Dutch SUDS by Boogaard *et al.* (2006), who found that the technical knowledge on SUDS is often still limited when implemented.

3.5.1.5. Root cause 5: lack of experience in constructing SUDS. As SUDS are relatively new and still developing, the interviewees mentioned that constructors often have limited experience in the installation of such systems. Moreover, the construction of SUDS is less straightforward than that of sewer networks: there are many different types of SUDS and their construction depends on case-, as well as location-specific conditions. The lack of experience makes it harder for constructers to anticipate the diverse conditions, and at the same time, the diversity complicates the gaining of general construction experiences with SUDS.

In addition, one of the interviewees explained that municipalities frequently hire external consultants to represent the municipality for construction supervision. This increases the risk of construction failures, as the external people often have limited background knowledge of the systems and their requirements. Hence, in addition to the experience of constructors, the experience of contractors and/or supervisors is crucial to the proper functioning of SUDS (Moglia *et al.* 2011).

3.5.1.6. Root cause 6: fitting SUDS to unforeseen circumstances. This root cause relates to the adjustment of the layout or design of SUDS due to circumstances that were not anticipated in the design phase. Existing urban infrastructure, both below and above the ground (e.g., cables, pipelines, or trees), could physically limit the construction possibilities. This problem is particularly severe in areas without detailed geological surveys or systematic infrastructure records. To deal with the 'unpleasant surprises', workers could then decide to make small adjustments to the design, such that they can continue the construction process. These adjustments, however, could significantly reduce the functionality of SUDS.

This root cause was also found in previous research by Moglia *et al.* (2011), who stated that in the construction phase of SUDS, the conditions often turned out to be different than expected. Based on, for instance tacit knowledge, (experienced) contractors then decided to change the design.

3.5.1.7. Root cause 7: actual use of SUDS by humans. This root cause relates to the actual use of SUDS in practice: after implementation, people could use the SUDS in a way that was not accounted for in the design.

Figure 6 | Case #33 has been assigned the root cause *Incomplete knowledge* about the internal technical processes. The pavers were separated by joints filled with a permeable material, allowing water to infiltrate. Even after a small rainfall event, however, water remained ponding for at least 1 h. As such, it was thought that the permeable material had become clogged, leading to a malfunction of the SUDS.

They could, for example, put a flowerpot in the gutter (Figure 7). The rain pipe collects the storm water from the roof and discharges the storm water into the gutter at street level. The water is then transported overland, and thus kept visibly (as opposed to the traditional subsurface lateral house connection), toward the infiltration facility. When placing a flowerpot in the gutter, the intended flow path of the storm water is blocked.

This root cause may stem from the fact that citizens are only limitedly aware of the concept of SUDS, as well as their role in the functioning of SUDS (Roy *et al.* 2008). In addition, Zhang & Chui (2018) showed that the willingness of the (uninformed) public to be involved in SUDS practices is not self-evident: they identified the *lack of public interest* and *lack of public support* as two significant barriers to the implementation of SUDS.

3.5.1.8. Root cause 8: poor communication between different project phases. This root cause refers to the poor communication between actors involved in different phases of the development process, i.e., the design, construction, and user/maintenance phase. One interviewee mentioned that it sometimes happened that, although technical drawings displayed the new design, e.g., a road design that ensures proper drainage of the runoff to an infiltration facility, it was still built according to traditional means.

This also relates to the fragmentation of the current urban planning process, resulting in the loss of information or knowledge during the transition from one project phase to the next (see, e.g., de Graaf & van der Brugge 2010).

3.5.1.9. Root cause 9: lack of knowledge how to maintain SUDS. Root cause 9 refers to the incomplete knowledge of operators on how to properly maintain SUDS. Five interviewees stated that operators are not always acquainted with the maintenance required for new systems. This could lead to incorrect or too little maintenance, ultimately resulting in the malfunctioning of SUDS. The work of Boogaard & Rombout 2008 supports this finding: they concluded that Dutch municipalities are often not aware of the maintenance requirements of SUDS.

3.5.1.10. Root case 10: poor maintainability of SUDS. This root cause refers to the sometimes-limited possibilities for maintenance, for instance, due to the inaccessibility of (some parts of) SUDS. This finding is in line with previous empirical research: Boogaard & Rombout (2008) stated that many infiltration facilities are difficult to inspect and clean. They argued that the maintainability of SUDS is key to their functionality, and that it should therefore be considered in the design phase.

3.5.1.11. Root cause 11: ambiguity about the maintenance responsibilities. It is often unclear who is responsible for the maintenance of SUDS. This ambiguity typically stems from the system interfaces (see Section 3.3.) that emerge with the shift to integrated urban water solutions. In addition, the construction of SUDS may lead to shifting responsibilities. This implies that a significant role in the maintenance of SUDS could be with parties whose key-priority is not water-related, like road authorities in the case of permeable pavement.

Figure 7 | Case #8 has been assigned the root cause actual use of SUDS. A flowerpot was placed in front of a dwelling's water outlet, preventing water to be discharged properly.

3.5.2. Reflection on the nature of the root causes

Looking at the list of root causes as a whole, Table 7 reveals that the root causes are mainly socio-institutional, rather than technical in nature. Hence, root causes typically relate to behavior of actors or the institutions that direct the perceptions and actions of these actors, concerning issues such as communication, responsibility, knowledge, experience, routines, and guidelines.

On the one hand, this finding could result from the phrasing of the root causes. For example, for the root cause 3, 4, and 10 (respectively, *incomplete knowledge about the interaction of SUDS with other urban systems*, *incomplete knowledge about the technical performance of SUDS*, and *poor maintainability of SUDS*), one could argue that the root causes are (mainly) related to the physical infrastructure. However, also for these root causes, we see a clear relationship with actors and institutions, i.e., that failures could be prevented by, e.g., better instructions, communication between actors or through evaluation.

On the other hand, the reason that we mainly identified root causes related to actors and institutions might be that SUDS are still relatively new. Most of the SUDS in our database are not yet at the end of their technical lifetime, suggesting that our list is not (yet) exhaustive. While our list of root causes could thus be further extended, Table 7 nevertheless shows that the socio-institutional system is a significant contributor to malfunctioning SUDS. This suggests that the socio-institutional infrastructure is not always properly aligned with the techniques and technologies used in SUDS, and that failures could be prevented if matters such as communication and guidelines would be given more attention.

3.6. Relationship between the root causes and case characteristics

3.6.1. Root causes versus failing function

Figure 8 gives for each of the root causes a breakdown of the number of cases by the different hydraulic functions of SUDS (*conveyance*, *infiltration*, and *storage*). This reveals that the different SUDS types are not equally affected by the root causes.

On the one hand, Figure 8 shows that 10 out of the 11 root causes have been assigned to more than one of the SUDS' functions, illustrating that root causes are not necessarily function-specific. On the other hand, Figure 8 reveals that some causes were frequently assigned to particular types of systems, while these causes were not (or not often) identified for the other systems. This suggests that there is a relationship between specific root causes and the hydraulic principles of SUDS (i.e., infiltration systems process storm water by means of infiltration, and conveyance systems process water through draining it via above-ground structures).

Based on this information, specific recommendations for each of the system types could be made. For example, root cause 4, *incomplete knowledge about the technical performance of SUDS*, is the most common root cause for infiltration systems ($n = 10$), while this root cause has not been assigned to conveyance systems (and has only

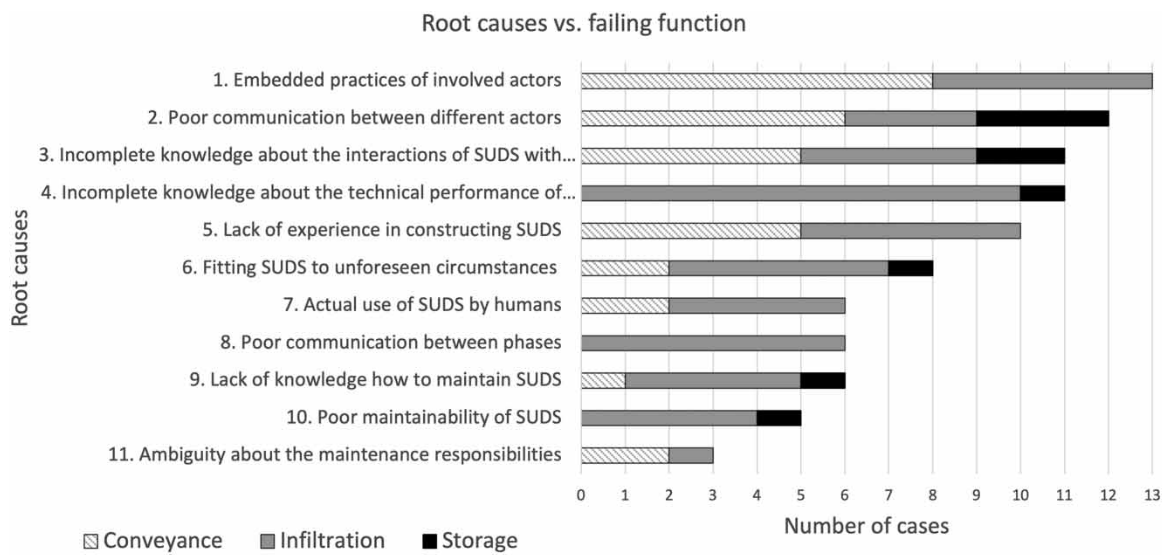


Figure 8 | Number of failures in SUDS of a certain failing function for each root cause.

been assigned to one failing storage system). Hence, information on technical performance is of particular importance for infiltration SUDS.

In addition, Figure 8 shows that the root causes 1, 2, 3, and 5 (respectively, *embedded practices of involved actors*, *poor communication between different actors*, *incomplete knowledge about the interaction of SUDS with other urban systems*, and *lack of experience in constructing SUDS*) are the most common root causes for failing conveyance systems. These four root causes are all related to the interaction and involvement of non-water-related actors, suggesting that the performance of conveyance SUDS is dependent on the actions of other actors. Conveyance systems process storm water through above-ground drainage and therefore interact with many other infrastructures in the urban environment (e.g., roads, curbs, gardens, speed bump, and lampposts), as well as their responsible actors. This suggests that, to minimize failures in conveyance systems, both the physical and socio-institutional interfaces between SUDS and other urban systems deserve extra attention.

3.6.2. Root causes versus phase of failure

Failures can origin from the design or construction phase, or sometimes they arise later during the user/maintenance phase. Figure 9 maps, per root cause, the number of failures that origin from each of the project phases, providing insights into which issues need most attention in particular project phases.

For the design phase, four root causes (numbers 1, 2, 3, and 4) were identified as the most common causes underlying technical failures: *Embedded practices of involved actors*, *Poor communication between different actors*, *Incomplete knowledge about the interactions of SUDS with other urban systems*, and *Incomplete knowledge about the technical performance of SUDS*. These four root causes mainly relate to the interaction of actors with the technical system. Conventional storm water systems are well developed from a socio-technical perspective, which is still progressing for SUDS. This suggests that, for the design of SUDS, it is crucial that the social system is interconnected with the technical system.

With respect to the construction phase, we found that technical failures are most often caused by the *Lack of experience in constructing SUDS* (root cause 5). This illustrates the importance of involving constructors in the implementation of SUDS: new systems do not only require advanced knowledge from engineers and designers, but also require different skills and knowledge from constructors. Hence, more attention should be paid to educate constructors about, e.g., what the new techniques and technologies entail, why new requirements are set, and what the critical issues for construction are.

With respect to the failures originating from the user and maintenance phase, Figure 9 reveals that the most dominant root causes are 7, 9, and 10: *Actual use of SUDS*, *lack of knowledge how to maintain SUDS*, and *poor maintainability of SUDS*, respectively. All these root causes relate to a certain lack of knowledge from users and operators on how to handle SUDS. Actors in charge of maintenance have to be well involved such

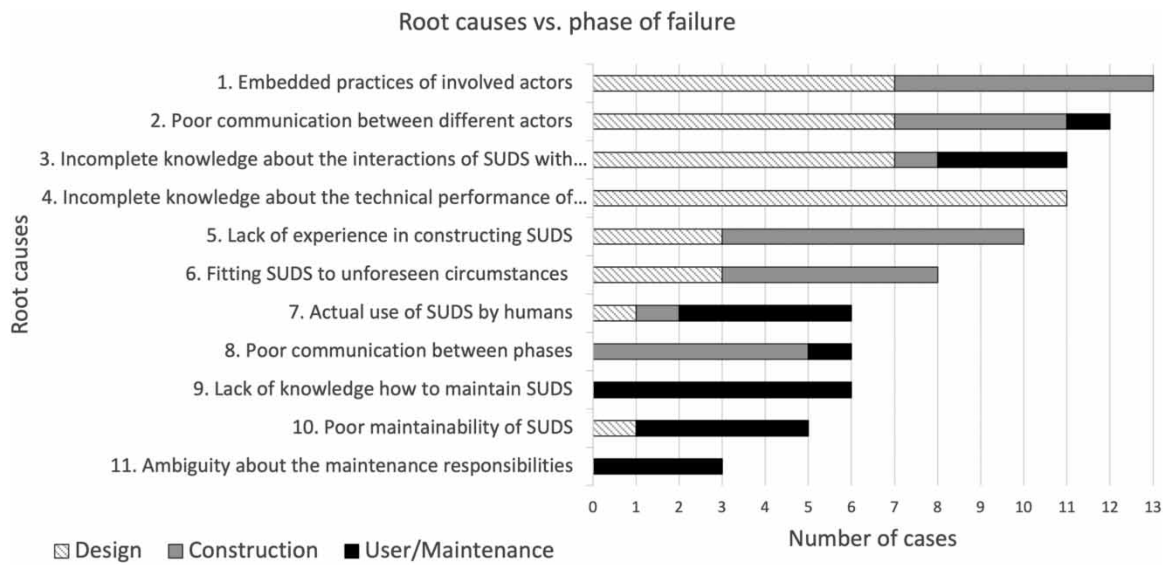


Figure 9 | Number of failures that origin from each of the project phases, per root cause.

that they know what maintenance is required for certain types of systems and how these maintenance practices should be performed.

Overall, Figure 9 reveals that all three project phases are important to consider for the development of new systems: root causes have been assigned in the same order of magnitude to each of the project phases, and eight out of the eleven root causes appear in two or more project phases. Hence, root causes can, in many cases, not be attributed to just one project phase. For example, *Poor communication between different actors* (root cause 2) can lead to failures in the design phase, but also in the construction and maintenance phase. In addition, root cause 9, *Lack of knowledge how to maintain SUDS*, which (in this research) has only been assigned to failures in the maintenance phase, illustrates that even if SUDS are well designed and implemented, failures can still occur in the user and maintenance phase.

3.6.3. Root causes versus failure location

Technical failures occur at several locations within SUDS (see Figure 2). We identified 11 failure locations (see Table 5) and grouped these into two categories: internal failure locations (failures occurring within a single urban system) and interface failure locations (failures occurring at the physical interface between two systems). Figure 10 combines these data with data on the root causes, showing that nine out of the 11 root causes occurred at both internal and interface locations. This reveals that to prevent the malfunctioning of SUDS, both these locations deserve attention in preventing SUDS failures.

In addition, with respect to the interface locations, Figure 10 shows that the most dominant root causes are numbers 1, 2, 3, and 5 (*Embedded practices of involved actors*, *Poor communication between different actors*, *Incomplete knowledge about the interactions of SUDS with other urban systems*, and *Lack of experience in constructing SUDS*). All these root cause relate to social aspects (i.e., skills and knowledge), suggesting that the failures at the interfaces of SUDS are often socio-institutional in nature, rather than strictly technical.

For the internal locations, we found that root cause 4 (*Incomplete knowledge about the technical performance of SUDS*) was clearly the most dominant one: it was assigned to 11 cases. Apparently, due to a lack of information about their functioning, SUDS frequently fail. To prevent such failures, we argue that malfunctioning should be anticipated, i.e., through investigating the failure and evaluating the SUDS in its real-world environment. Such evaluation is key to improve the performance of SUDS, providing information on how to adapt the SUDS. Documenting and sharing this information fosters learning, eventually contributing to the reliability of SUDS.

4. CONCLUSION AND OUTLOOK

SUDS are widely implemented systems that form an essential part of contemporary storm water management. Like any other part of the urban water infrastructure, piped or non-piped, SUDS are subject to failure. Based

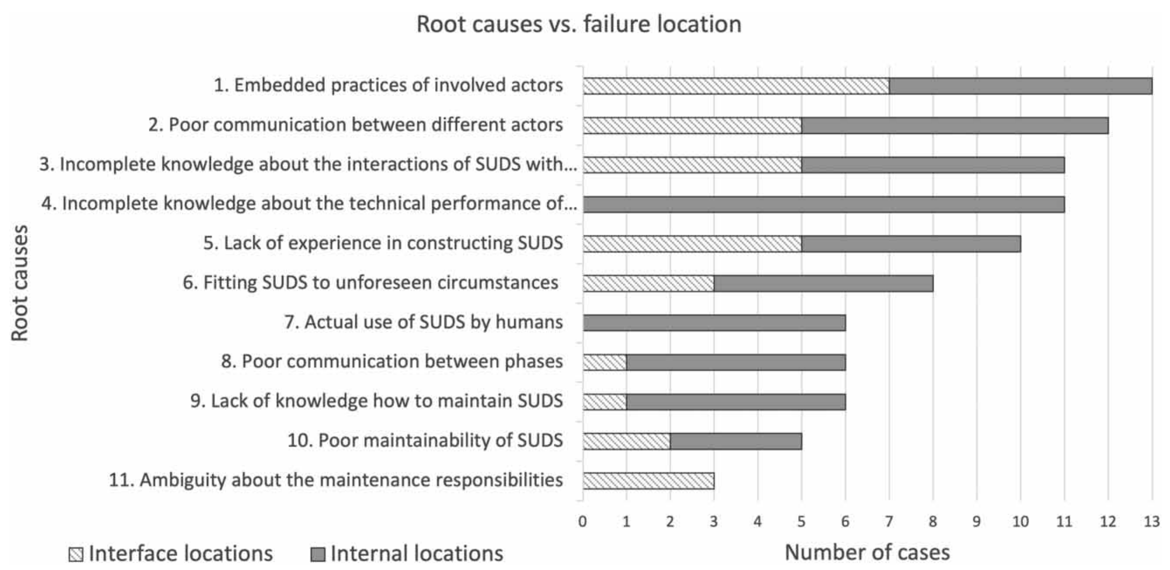


Figure 10 | Number of failures in SUDS failure location, for each root cause.

on observations, this exploratory study has identified 70 failure cases in various types of SUDS in 11 Dutch municipalities. The analysis of these failure data reveals that:

- failures often (more than one-third) occur at the interfaces of different urban systems, i.e., where the physical infrastructures of two urban systems meet, such as at the interface between a private plot and a public street;
- failures affect each of the defined hydraulic functions of SUDS: infiltration, conveyance, and storage, with, respectively, *clogging*, *interference with obstacle*, and *limited freeboard* and *interference with obstacle*, as the most noticed failing functions;
- failures can origin from the design phase, construction phase, as well as the user/maintenance phase.

These findings suggest that a decent SUDS construction check upon completion (thereby also considering the user/maintenance phase, as well as the transfer between phases) has the potential to reduce the number of failures. Special attention should be paid to the interfaces with other urban systems (e.g., green, roads, and private plots).

Based on interviews with urban water professional, we have identified a final list of 11 causes underlying these failures, with all failures being linked to one or two of the root causes. The most common root causes identified are:

- embedded practices of involved actors,
- poor communication between different actors,
- incomplete knowledge about the interactions of SUDS with other urban systems,
- incomplete knowledge about the technical performance of SUDS, and
- lack of experience in constructing SUDS.

Several of the most common root causes are merely socio-institutional, rather than technical in nature. This suggests that not only the physical interfaces that arise with the shift to SUDS, but also the socio-institutional changes that this shift requires should be addressed. To define *how* they should be addressed (for instance, by implementing new guidelines and standards, or particular policy instruments, or by changing decision-making processes), further research should identify what the social-institutional nature of causes can be attributed to. For example, to the time it takes for institutions to become embedded, i.e., to develop new practices, skills, and knowledge, or to the inherently more integrated character of SUDS compared with traditional sewer systems, i.e., next to water managers, various other 'professional' actors, as well as inhabitants play an important role in SUDS. Furthermore, we argue that additional interviews with professionals from other disciplines and sectors, such as landscape architects and urban planners, could provide valuable insights and may lead to other, new, root causes that our approach has not been able to reveal.

Finally, we encourage further research on the performance of SUDS in practice, with, for instance, different viewpoints, levels of detail, and/or local conditions. Our study provides valuable insights into the occurrence and root causes of failures in SUDS and thereby contributes to a renewed socio-technical urban water system with more sustainable water management practices. We invite other researchers to analyze other sustainable storm water systems, to foster learning, anticipate failures, and improve the performance of SUDS in practice.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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