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Failure mechanisms in blue-green infrastructure: permeable pavements, bioswales and retention ponds in the Netherlands

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ABSTRACT

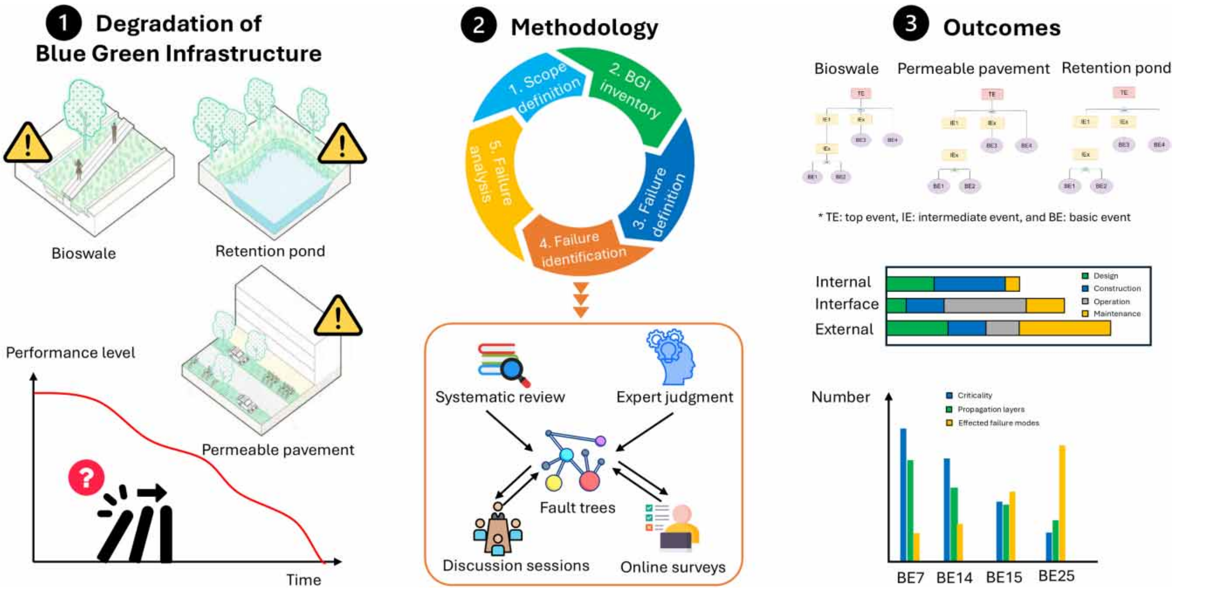
Blue-green infrastructure (BGI) plays a significant role in the resilience of Dutch cities to the rising societal challenges and climate change effects. However, their condition is often neglected by asset managers, possibly resulting in operational failures and rapid deterioration. This research aims to identify the failure mechanisms of three commonly used BGI systems (permeable pavements, bioswales and retention ponds) during their whole life cycle. A comprehensive review of literature was conducted first, along with experts' assessment. Fault tree analysis was used to explore failure modes, degradation processes and root causes. Root causes were evaluated through minimal cut sets analysis and ranked by their criticality, propagation and impact. The findings were validated by a team of experts and structured in three fault trees accounting for 400 possible failure mechanisms: 84 for retention ponds, 115 for permeable pavements and 201 for bioswales. Clogging and hydraulic overloading emerged as key failure mechanisms in permeable pavements and bioswales, triggered by diverse root causes. Failures in retention ponds are largely linked to permanent pool conditions. The results provide a foundation for developing standardized inspection and monitoring protocols that address current gaps in the asset management of BGI.

Key words: asset management, fault tree analysis, malfunction, nature-based solutions, qualitative analysis, root causes

HIGHLIGHTS

- A total of 224 unique root causes of failures in three analysed BGI systems were identified.
- All components of the analysed BGI systems are vulnerable to failure.
- Most root causes originate from the BGI itself.
- BGI systems are highly sensitive to internal design and the urban environment in which they operate.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The Dutch climate adaptation strategy has identified six urgent risks: heat stress, frequent failures in the transport system and underlying infrastructure, more frequent damage to agricultural activities, loss of biodiversity, increased health burden and other cumulative effects (Meijs *et al.* 2018). Traditional adaptation strategies, such as enlarging sewer systems, are impractical options as they are expensive to implement and maintain, and provide typically one primary function (Zabicki 2018). Blue-green infrastructure (BGI) systems have become a more attractive option due to their efficiency in addressing societal challenges and sustainability (Tang *et al.* 2018). They are designed as an urban mechanism that integrates nature and natural processes into conventional infrastructures (Tang *et al.* 2018). The list of provided services is quite diverse and extensive (O'Donnell *et al.* 2020). Their integration with traditional urban drainage systems can enhance the resilience to incidents and unusual events (Ertl *et al.* 2024a). Therefore, new policies and regulations are advocating for BGI systems, and they are increasingly applied worldwide (Tang *et al.* 2018).

1.1. Failure mechanisms of BGI

BGI systems, like any other urban infrastructure, are prone to failure. After installation, they often receive insufficient or no maintenance, resulting in diminished functionality or complete failure over time (Blecken *et al.* 2017). Literature and manuals such as the CIRIA manual (Woods Ballard *et al.* 2015) mainly focus on the design, placement, construction, development and improvement of BGI. However, BGI needs to be operated, maintained and rehabilitated to ensure the intended long-term performance (Langeveld *et al.* 2022).

Considering the broad list of services, BGI is normally integrated into the built environment. A wide spectrum of hybrid systems that combine 'grey' and 'green' infrastructure has emerged, incorporating tailor-made designs (Cherqui *et al.* 2024). The boundaries of such systems include changes in physical surface, height difference and designed process, which increase the system's susceptibility to failure (Nieuwenhuis 2023). Vollaers *et al.* (2021) found that failure of BGI can originate at any phase throughout its entire life cycle, and the interface with the urban environment is the main location of failure. Documented experience with long-term functioning in the Netherlands is relatively limited (Rombout *et al.* 2007). Therefore, failure mechanisms remain normally complex and ambiguous for asset managers.

To evaluate the current state of research on BGI failures, a systematic review of literature was conducted on 1 November 2025, using the SCOPUS database (Elsevier 2025). Since the topic has a multiplicity of names, it has been represented by a set of keywords. The query included the combination of the terms 'Failure,' 'Fault' and 'Malfunction' with 'Permeable Pavement', 'Bioswale' and 'Retention Pond'. Most of the generated results were not related to failure mechanisms (or the cause-and-effect relation), and the only publication explicitly dedicated to this topic was published by Bahrami *et al.* (2024). Therefore, the search process has been expanded to include other types of literature, such as academic theses, technical reports and guidelines.

Manuals and guidelines (such as Erickson *et al.* 2013; Woods Ballard *et al.* 2015; Ertl *et al.* 2024b) offer either implicit or incomplete descriptions of the common failure mechanisms. They provide valuable insights into the occurrence, consequences and root causes based on documented practical experience and existing research. However, the primary emphasis is typically on the planning, design, construction and maintenance, indicating the need for further investigation.

Many desktop studies employ different types of analyses to investigate the root causes of specific failures. For instance, Radfar & Rockaway (2016) conducted a sensitivity analysis to investigate the relation of permeable pavement clogging with rainfall variables and maintenance activities. Razzaghmanesh & Beecham (2018) reviewed the methods used to investigate the controlling factors that can potentially affect the start and progression of clogging in permeable pavements. Zabicki (2018) used the Pearson coefficient to statistically investigate the correlations between the infiltration capacity of permeable pavements and factors related to the facility and the surrounding environment. A major limitation of desktop studies, however, is that correlation analysis does not always provide proof for failure causes.

Field studies, on the other hand, offer valuable insights into the occurrence and the root causes of failures. For example, Hirschman & Woodworth (2010) carried out a field assessment of around 200 BGI in Virginia's James River watershed, USA, and isolated critical design, construction and maintenance factors that 'make' or 'break' the performance and longevity. DelGrosso (2018) analysed 3,141 inspection and maintenance records for multiple types of BGI in Fairfax County, Virginia, USA, to investigate the effects of local site-conditions and the level of routine maintenance on the frequency of facility deficiencies. Most of the detected deficiencies are attributed either to the inadequate pre-treatment or improper construction. Vollaers *et al.* (2021) counted 70 failure incidents across 11 Dutch municipalities, attributed to 18 technical failures and primarily driven by 11 unique root causes that have a socio-institutional nature rather than technical. Kavehei *et al.* (2023) assessed the condition of 194 bioretention basins and identified key factors influencing their performance. Filter media and grey components were found to be particularly vulnerable, primarily due to inefficient sediment forebays, issues with inlet and outlet infrastructure, sediment accumulation on the filter media, low permeability, limited plant diversity and inadequate vegetation cover.

Bahrami *et al.* (2024) reviewed the scientific literature and investigated the potential failure mechanisms in bioswales, rain gardens and green roofs using fault tree analysis (FTA). The authors categorized the BGI systems into common components and eight component groups based on the similarity of roles. They grouped the delivered services into three categories: runoff quantity control, runoff quality control and additional functions. The resulting three trees consist of 54 basic events and 45 intermediate events. Bahrami *et al.* (2024) can be seen as a starting point for further exploration of failures of BGI. Further work is necessary, among others, to extend their failure trees to the surroundings of the BGI and to add other BGI not considered.

Consequently, asset managers often rely on personal judgement or adopt a run-to-failure approach, guided by an inadequate understanding of the long-term performance and management requirements of BGI systems. This practice contributes to the progressive degradation and, ultimately, the functional failure of bioswale systems (Langeveld *et al.* 2022).

Given the above, the aim of this research is to fill the gaps in knowledge regarding the failure mechanisms of BGI, their interdependencies and consequences for the end user. We are deliberately focusing on three common BGI systems that are in widespread use (permeable pavements, bioswales and retention ponds) as this will allow us to investigate failure mechanisms in more detail. The results obtained this way will contribute to the advancement of BGI asset management, leading to better failure detection, data collection, performance assessment and maintenance activities.

2. METHODOLOGY

The methodology, presented in Figure 1, comprises five key steps:

2.1. Scope definition

Permeable pavements, bioswales and retention ponds have been selected, as they are extensively applied in the Netherlands. They incorporate a wide range of solutions addressing different aspects of urban water

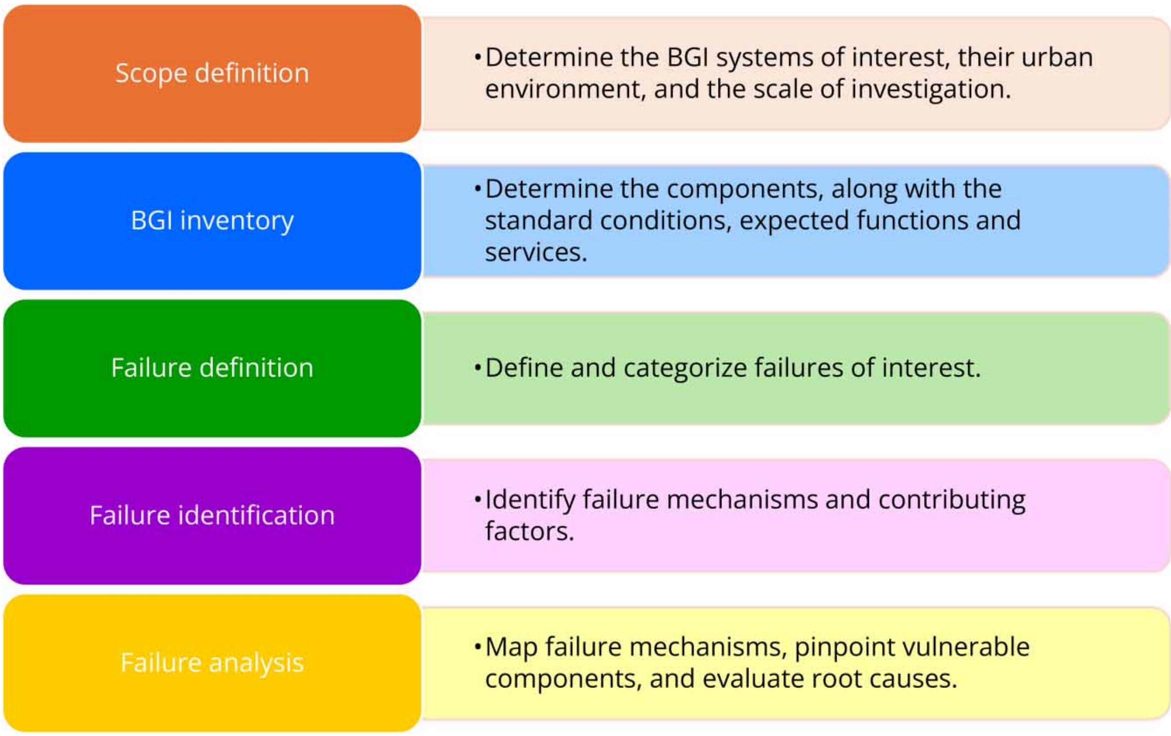


Figure 1 | Overview of the research methodology.

management, multiple spatial scales and diverse ownership structures, and reflect the typical challenges in the asset management of BGI in the Netherlands.

The BGI systems have been analysed using three perspectives (Auger *et al.* 2024):

- from the asset-based perspective, to understand their unique and common failure mechanisms;
- from the system-based perspective, to investigate the failure mechanisms during the dynamic interaction of BGI with the urban drainage system and
- from the urban fabric perspective, to investigate the contribution of urban planning and urban development in the drainage basin to BGI failure mechanisms.

In Dutch urban areas, permeable pavements are normally combined with road surface or parking spaces, bioswales are placed alongside roads or parking spaces and retention ponds are located at land depressions. Stormwater typically drains from the house roof, through the garden, the garage and impermeable pavement towards the permeable pavement to be infiltrated into groundwater. The excess overflow is collected and treated by the bioswale, and either infiltrated into the groundwater or conveyed to the retention ponds for storage and further treatment (Figure 2).

2.2. BGI inventory

In the Netherlands, there are no standardized national guidelines for the asset management of BGI systems. Municipalities are primarily responsible for the design, construction and management of local infrastructure and public space. National laws establish legal requirements related to safety, environmental performance and procurement processes, and they do not prescribe exact design templates. National frameworks, such as CROW guidelines (CROW 2023) and the RAW system (CROW 2025), serve as non-mandatory standards and provide technical specifications and best practices. This means municipalities can adopt alternative designs for features, like bioswales, permeable pavements or retention ponds to reflect local conditions, sustainability goals or aesthetic preferences, even if these differ from typical standards.

To overcome the challenges raised by the uniqueness and diversity of BGI, as well as the tailor-made designs and integrations, BGI systems can be divided into basic and additional components. This approach allows the inventory of relevant components and specifies their expected roles.

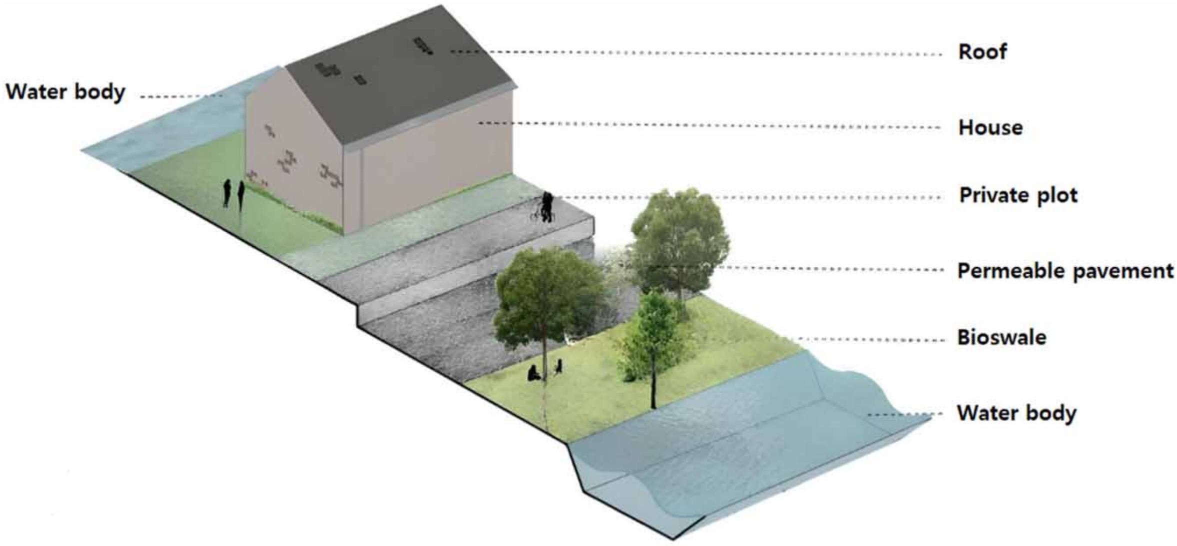


Figure 2 | A standard urban context showing the interface between BGI systems and their surroundings (modified after Vollaers *et al.* (2021)).

By 'standard' designs, we refer to those which are incorporated into municipal guidelines, widely applicable and integrated into urban planning and policy frameworks. General designs of permeable pavements, bioswales and retention ponds are illustrated in Figure 3, along with a comprehensive list of services presented in Table 1. Tables 2–4 collectively synthesize the key and ancillary components of permeable pavements, bioswales and retention ponds, linking ideal design and maintenance conditions to their functional roles in urban stormwater management. Permeable pavements primarily emphasize infiltration, storage and water purification while maintaining structural capacity, whereas bioswales integrate hydrological regulation with ecological functions through vegetation-driven processes such as pollutant uptake, soil stabilization, biodiversity enhancement, carbon sequestration and aesthetic improvement. Retention ponds further extend these functions by providing sustained attenuation and sedimentation. Collectively, modular and supplementary elements across the systems enable adaptability to site-specific conditions and improved performance during extreme operating conditions.

2.3. Failure definition

Clear definitions and thresholds are necessary to identify and categorize failure types through the literature review and experts' assessment.

Many failures result from gradual deterioration, which refers to a wide spectrum of processes and a sequence of events that are time-driven and affect the condition, performance, functionality and/or the provided services of a component, part of a system or the whole system. Under this definition, a variety of complications hinder our understanding of BGI deterioration: (1) Limited knowledge about the involved processes and events. (2) The diversity of encountered processes, which can be physical, chemical, biological and combinations or sequences of these. (3) The complexity and uniqueness of BGI (Barraud *et al.* 2024).

Deterioration progressively evolves until a level where the asset fails to meet the designed condition, performance, function or service. Conditional failure occurs when there is a physical deterioration or damage that affects the structural integrity, such as corrosion, cracking or collapse. Performance failure is a decline in an asset's ability to operate above the designed threshold, e.g. reduced hydraulic performance in a bioswale due to sediment accumulation. It is often expressed in terms of efficiency, reliability and resilience. Functional failure refers to the complete inability of an asset to deliver its technical role, such as a bioswale that cannot infiltrate water due to filter basin sealing. A system may continue to function even when its performance has declined. Service failure occurs when the asset fails to meet the expectations or needs of stakeholders, such as street flooding caused by a malfunction in the infiltration of bioswales.

Sudden failures can also occur, though they are less common and usually linked to a shock event or unexpected disruption, such as the collapse of a weir or check dam due to poor installation or vandalism. Those failures occur without warning and can lead to safety hazards or costly damage.

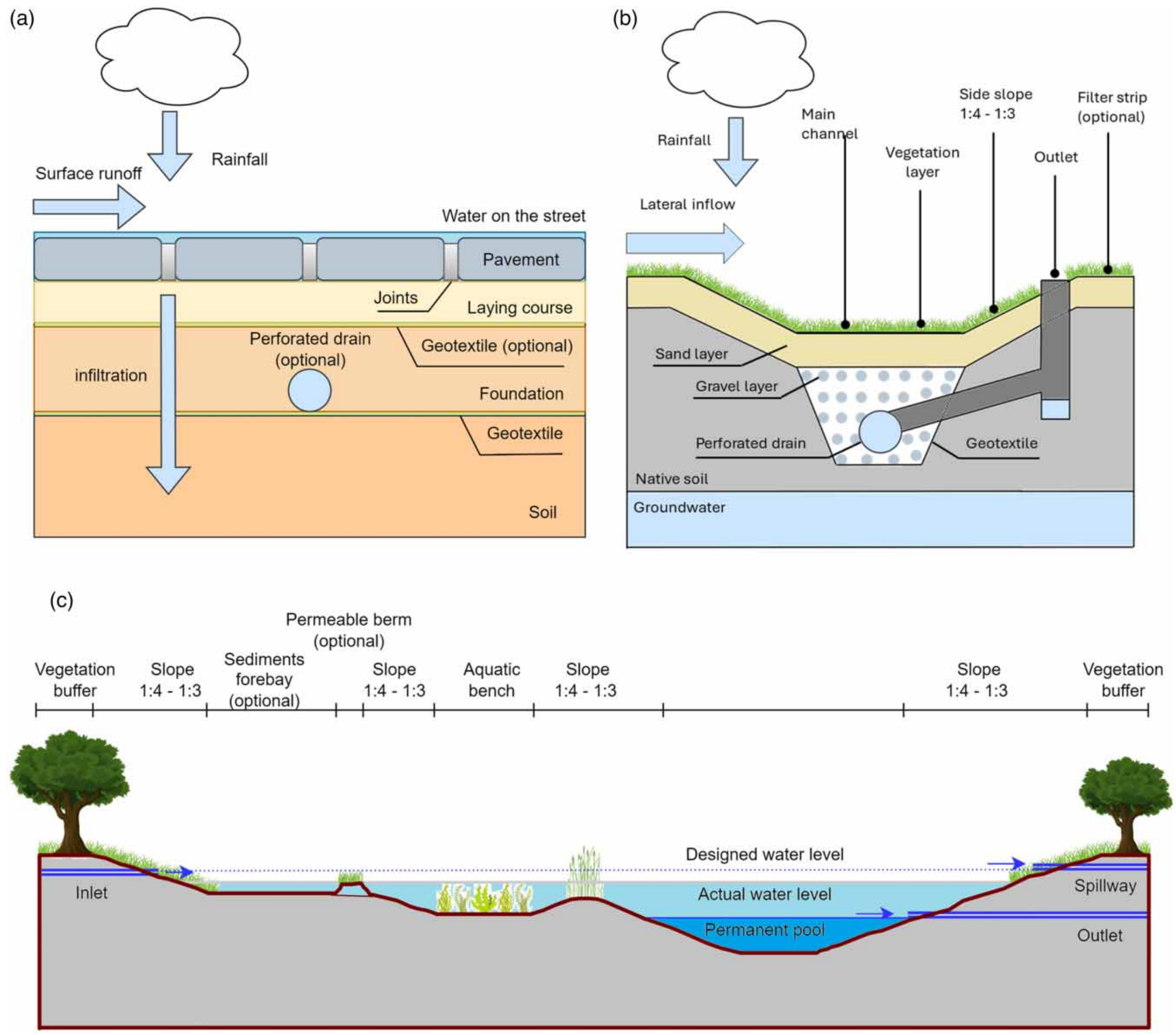


Figure 3 | Standard cross-section of (a) permeable pavement (modified after Rombout *et al.* (2007)), (b) bioswale (modified after Utrecht Municipality (2021)) and (c) retention pond (modified after Woods Ballard *et al.* (2015)).

There is currently no consensus across local, national or international public spaces guidelines regarding failure thresholds for BGI, as shown in Table 5. Moreover, many types of failure remain unidentified in existing management and maintenance manuals.

Veldkamp *et al.* (2020) evaluated the hydraulic performance of permeable pavements at 67 sites within 11 Dutch municipalities and found that infiltration rates ranged from 35 to 5,707 mm/h. The differences across these values are significant, reflecting different functional contexts or base scenarios. Additionally, stakeholders' perception varies considerably based on their expectations and the intended purpose of the project. Some are satisfied with infiltration values exceeding the threshold of 20.8 mm/h, while others are not satisfied even with higher values. This emphasizes the importance of a standardized guideline for public spaces, along with a consistent inspection and monitoring protocol, to promote standardization and best practices, address data gaps and limitations, facilitate data sharing, inform policy updates and support evidence-based decision-making.

To address the current inconsistencies and the lack of standardized definitions for failures and their thresholds, this study adheres to the Dutch hierarchical framework. Municipal guidelines are prioritized, as they best reflect local conditions and context. In the absence of local specifications, national guidelines are followed, and if those are unavailable, international guidelines are applied.

This study distinguishes between grey (traditional built infrastructure, e.g. headwall inlet of a bioswale) and green components (natural-based elements, e.g. vegetated filter basin of a bioswale). The conditional failures of grey components are assessed based on the Dutch standards for condition assessment of buildings and

Table 1 | Standard list of services of permeable pavements, bioswales and retention ponds (modified after European NWRM+ Platform (2013), Woods Ballard *et al.* (2015) and Roghani *et al.* (2025))

Ecosystem service type	List of Services	Permeable Pavements	Bioswales	Retention Ponds
Provision	Allow traffic	Primary	None	None
	Water Reuse Potential	Secondary	Secondary	Primary
	Recreational Opportunities	None	Secondary	Primary
Regulating water quantity and flood control	Stormwater Management	Secondary	Primary	Primary
	Flood Risk Management	Secondary	Primary	Primary
	Reduction in combined sewer systems	Secondary	Primary	Primary
	Extend grey urban drainage system Lifespan	Primary	Secondary	Secondary
	Groundwater Recharge	Primary	Primary	Secondary
Regulating water quality and soil protection	Erosion control	None	Secondary	Primary
	Sediment Control	None	Primary	Primary
	Improved Surface Water Quality	Secondary	Primary	Primary
	Groundwater Quality Protection	Secondary	Primary	Secondary
	Improved Soil Quality	Primary	Primary	Secondary
Regulating climate, air and noise	Temperature Regulation	Primary	Secondary	Secondary
	Localized Cooling Effect	Secondary	Secondary	Primary
	Urban Heat Island Mitigation	Primary	Secondary	Secondary
	Improved Air Quality	Secondary	Primary	Secondary
	Noise Reduction	Secondary	Secondary	Secondary
	Carbon Capture	None	Secondary	Primary
	Carbon Footprint Reduction	Secondary	Secondary	Primary
	Biodiversity Enhancement	None	Primary	Primary
Supporting and habitat	Resilience to Climate Change	Secondary	Primary	Primary
Cultural and socio-economic	Aesthetic Enhancement	None	Primary	Primary
	Compliance with Environmental Laws	Secondary	Primary	Primary
	Community Value Enhancement	Secondary	Secondary	Primary
	Cost Efficiency Over Time	Primary	Secondary	Secondary
	Educational Value	None	Primary	Primary

Primary services: explicitly targeted by design; secondary services: arise as ancillary or co-benefits; and non-services: negligible or inconsistent.

Table 2 | Standard conditions and functions of components in permeable pavements (modified after Woods Ballard *et al.* (2015))

Components		Ideal condition	Functions
Basic	Pavement	No cracking No deformation Unclogged Free of debris and sediment	Allow traffic Collect and infiltrate excess rainfall and runoff towards the foundation Purify excess water
	Joint fill material	Even distribution No erosion or washout Unclogged	Stabilize pavement units Enhance infiltration
	Foundation	Strong matrix structure Sufficiently porous Adequate storage capacity No deformation or settling	Support the pavement Infiltrate water towards the geotextile Store infiltrated water temporarily Purify infiltrated water
	Geotextile	Good separation between foundation and subsoil Free of tears or punctures Unclogged	Prevents mixing of soils and maintains system integrity Infiltrate water and air Purify infiltrated water
	Emergency overflow	Properly positioned Unclogged	Manage overflow during extreme events
Additional	Liner	Waterproof Load resistance	Prevent infiltration where there is slope instability, foundation problems or high contamination
	Geotextile	Good separation between the laying coarse and the foundation Free of tears or punctures Unclogged	Prevents mixing of soils and maintains system integrity Infiltrate water and air Purify infiltrated water
	Perforated drainage pipe	No corrosion, leaks or deformation No blockages or debris.	Collect and convey excess water towards a surface body when infiltration is limited Prevent groundwater flooding and dewatering
	Internal check dams	Placed in the sub-base at regular intervals Enough water storage	Prevent water from bypassing the lower sections Slow subsurface flow and increased infiltration
	Tree grate	Properly aligned with the tree Allow infiltration Undamaged	Prevent soil particles from clogging the pavement Allow tree roots to absorb air, sunlight and water Allows the soil underneath to stay uncompacted

infrastructural objects, NEN 2767. The conditional failures of green components are assessed based on the methodology introduced by the Quality Catalogue of Public Space, KOR 2023.

Performance and functional failures are evaluated based on the municipal guideline for BGI systems, such as Gemeente Amsterdam (2024). In the absence of local specifications, the national guidelines suggested by Dutch knowledge institutes, such as RIONED (Stichting RIONED n.d.), STOWA (Hau *et al.* 2024) and CROW (CROW n.d.), are adopted. Otherwise, the international guidelines are followed, such as the CIRIA manual (Woods Ballard *et al.* 2015). Service failures, on the other hand, are evaluated based on public satisfaction, primarily indicated through reported citizen complaints.

2.4. Failure mechanism identification

This step focuses on the identification of key failure mechanisms for the three analysed BGI systems. Two sources of data have been used to establish these failure mechanisms:

(1) A list of 19 relevant works that have been published between 2014 and 2024 has been reviewed. Management and maintenance guidelines (e.g. Woods Ballard *et al.* 2015; CoP 2022) are the main sources of information used for this work. Other literature, such as technical reports and fact sheets (e.g. Leskens & Lekkerkerk 2020; Brolsma *et al.* 2022), offered real-world implementation data and practices, academic theses (e.g. Zabicki 2018; Nieuwenhuis 2023), highlighted local applications and performance monitoring strategies, while research papers (e.g. Boogaard *et al.* 2014; Veldkamp *et al.* 2022; Bahrami *et al.* 2024) provided insights into the underlying root causes.

(2) Experts' assessment has been employed to reveal implicit failure mechanisms or to bridge the gaps of uncompleted ones (see Figure 4).

Table 3 | Standard conditions and functions of components in bioswales (modified after Woods Ballard *et al.* (2015))

Components		Ideal condition	Functions
Basic	Inlet	Well-graded slope Stable and erosion-resistant No blocks, leaks or backflows	Direct stormwater inflow Reduces flow velocity to prevent erosion Seamless connection
	Vegetation	Native (no invasive weeds and plants) Well distributed (density, no bare spots) and height of plants <15 cm Healthy	Stabilize soil and enhance infiltration Filter pollutants through roots Aesthetic and habitat value Increase in biodiversity Carbon sequestration
	Filter basin (sand layer)	Well-graded slope Clean (no litter, debris or accumulated sediments) Sufficiently porous Adequate organic content Uniform and medium-grain sand	Direct stormwater inflow Infiltrate stormwater Support vegetation growth Remove fine sediments
	Geotextile	Good separation between the filter basin and the gravel layer Free of tears or punctures Unclogged	Infiltrate water and air Purify infiltrated water Infiltrate water and air
	Gravel layer	Strong matrix structure Angular gravel with consistent size distribution Adequate storage capacity	Support the filter basin. Enhance drainage Store infiltrated water temporarily to prevent clogging of the perforated pipe
	Perforated drainage pipe	No corrosion, leaks or deformation Perforation size appropriate for flow rate	Collect and convey excess water towards a surface body when infiltration is limited Prevent groundwater flooding and dewatering
	Outlet	Well-graded slope Stable and erosion-resistant No blocks, leaks or backflows	Regulate the discharge of excess stormwater to the downstream system and prevent backflow Prevent erosion Seamless connection
	Emergency overflow	Properly positioned Unclogged	Manage overflow during extreme events
Additional	Forebay	Proper sedimentation zone	Captures and settles coarse sediment and debris
	Screen	Fine mesh or grate Mounted vertically or at a 45° angle Even with a slope to avoid flow bypass or ponding	Filters out large debris and litter
	Energy dissipator	Installed on a geotextile base to prevent scouring	Reduces the velocity of incoming water
	Flow spreader	Flat or slightly depressed section Length spans the entire width of the bioswale	Evenly distributes incoming runoff
	Grass filter strip	Dense and low-growing grass Smooth slope and free of rills, depressions or bare spots	Pre-filters runoff from coarse particles
	Gravel diaphragm	Clean and uniform graded gravel	Spreads flow and filters sediments
	Flow divider	Installed in a stable and accessible location Allows for adjustable flow split	Splits incoming water to multiple treatment cells or routes of excess flow
	Check dam	Placed transversely across the swale at regular intervals Well-draining underlying soil No deformation or damages No erosion or washout around the structure	Slow water velocity Increased infiltration
	Weir	Height matches the targeted water detention depth Use notched (V or rectangular) weirs to fine-tune flow rates Levelling the top of the weir with emergency overflow	Control water levels Regulates outflow Allows overflow at a specific elevation

Table 4 | Standard conditions and functions of components in retention ponds (modified after Woods Ballard *et al.* (2015))

Components		Ideal condition	Functions
Basic	Inlet	Well-graded slope No blocks, leaks or backflows Stable and erosion-resistant Equipped with energy dissipators	Directs stormwater inflow Seamless connection Prevents erosion Reduces flow velocity
	Aquatic bench	Proper depth (0.3–0.5 m) Diverse and native aquatic plants	Supports aquatic plants and wildlife, acting as a biological filter
	Permanent pool	Maintains a standing water level (1–2 m)	For sedimentation and pollutant removal Supports aquatic life
	Attenuation storage volume	Adequate capacity	Temporary storage volume
	Outlet	Well controlled No blocks, leaks or backflows Stable and erosion-resistant	Regulates the discharge of excess stormwater to the downstream system and prevent backflow Seamless connection Prevents erosion
	Emergency spillway	Adequate capacity and properly positioned Unclogged	Manage overflow during extreme events
	Access path	Durable, clear and unobstructed	Provides access for maintenance and inspection activities
Additional	Safety bench	A suitable flat distance around the perimeter	Discourages direct access, facilitates surveillance of the pond and rescue, and acts as a maintenance route
	Sediment forebay	Adequate capacity Unclogged	Effective pre-treatment (traps coarse sediments and floating oils)
	Vegetation buffer zone	Dense and native vegetation surrounding the pond No invasive species or bare patches	Filters the surrounding landscape runoff and stabilizes soil
	Water circulation features	Adequate air provider Adequate water movement	Enhances aeration Prevents stagnation and sediments resuspension
	Embankments or dikes	Contain the pond	Provides structural stability

Table 5 | Minimum infiltration capacity for the permeable pavements

Source	Threshold value (mm/h)	Base scenario	Notes	Reference
CIRIA	2,500	Rainfall event: 250 mm/h [a] Runoff ratio: 1:2 [b] Safety factor: 10	For newly constructed pavements	Woods Ballard *et al.* (2015)
European standard Kiwa Netherlands	194.4	Rainfall event: 97.2 mm/h Runoff ratio: 1:4 Safety factor: 2	For newly constructed pavements	Zabicki (2018) Boogaard *et al.* (2014)
CROW	75.6–120.3	Based on the literature	Operational infiltration range	CROW (2019)
Rotterdam Municipality	40	(Local) rainfall event: 25 mm/h Runoff ratio: 1:1.85 Safety factor: 2	Maintenance trigger	Hout (2024)
RIONED	20	End-of-life/serviceability condition	Intervention point	RIONED (2019)

[a]Runoff ratio is the percentage of the permeable area to the impermeable area.
[b]Safety factor quantifies the buffer against failure beyond expected loads.

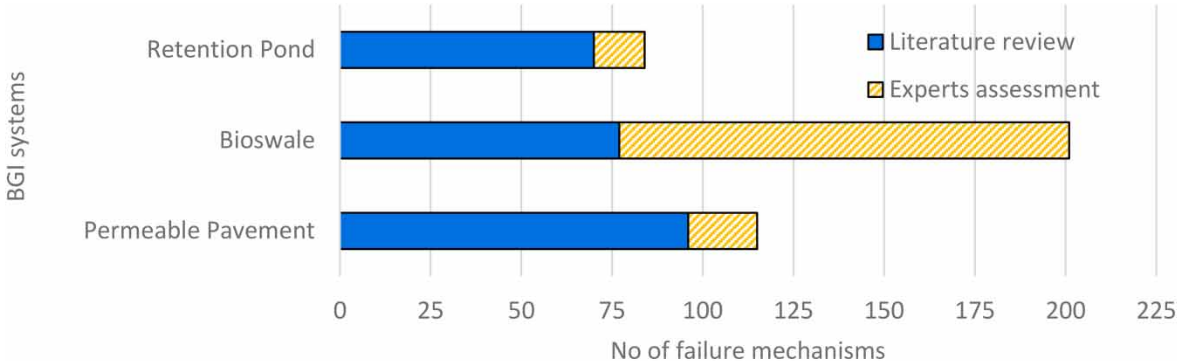


Figure 4 | Number and sources of reported failure mechanisms.

To reduce subjectivity and validate the identified failure mechanisms, expert consultation was conducted at the final stage of the study among the co-authors of this paper. The first round involved the professor and associate professor and was carried out through multiple discussion sessions, while the second round was conducted with three researchers via an online survey.

2.5. Failure analyses

2.5.1. Probable cause analysis

This step focuses on linking the root causes (Basic Events: BE) of identified failures to ultimate events affecting the end user (Top Events: TE) via deterioration points (Intermediate Events: IE) identified in the previous step.

The identified failure mechanisms for the three analysed BGI systems are mapped, as shown in Figure 5. This style of mapping was used due to its simplicity and ability to deal with complex problems (Barsalou 2014). The top-bottom approach starts with a top event, representing the failure mode, followed by a series of intermediate events representing the degradation states, and gates that describe the logical relationships between different intermediate causes and effects. The bottom events represent the underlying root causes that initiate the failure process (Pan *et al.* 2022).

2.5.2. Minimal cut set analysis

In a fault tree, a cut set is the combination of basic events that occur simultaneously and lead to the top event. The cut set becomes minimal if the basic events cannot be reduced without losing their ability to cause the top

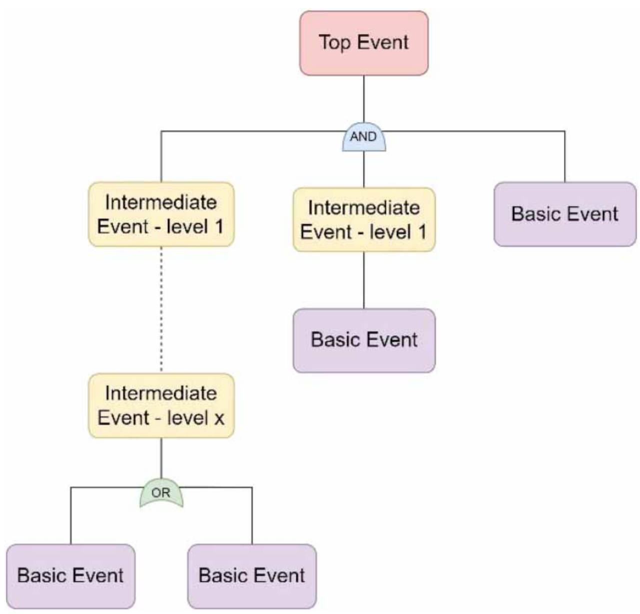


Figure 5 | Diagram of generic FTA (modified after Pan *et al.* (2022)).

event. The number of involved basic events denotes the order of the MCS. Lower-order MCS may indicate more critical failure mechanisms and should, therefore, receive higher priority in the risk management strategy (Bahrami *et al.* 2024). The results of MCS are a fault tree that is logically equivalent to the original tree and consists solely of OR gates, meaning that the occurrence of any one of the identified MCSs is sufficient to trigger the top event. In this way, the redundant basic events are not double-counted in the quantitative analysis.

2.5.3. Criticality analysis

This analysis aims to evaluate the relative importance of each MCS (or basic events) in causing the system failure and rank them accordingly. The criticality of a cut set is calculated based on the frequency of a basic event that appears in the first- or higher-order MCSs.

2.5.4. Cascade/propagation analysis

This analysis aims to understand the failure chain and system behaviour under stress. The path starting from the root cause towards the top event is analysed, and the propagation delay or amplification is assessed via the number of involved intermediate events.

3. RESULTS AND DISCUSSION

Three fault trees have been constructed for permeable pavements, bioswales and retention ponds. A summary is presented in Table 6, and the resulting trees, along with the details of the obtained events, are provided in the Supplementary material. An online version of the fault trees is also available at https://omaralmasalmah.github.io/Fault-trees/.

The fault tree of retention ponds is presented in Figure 6, with comprehensive descriptions of basic, intermediate and top events in Tables 7–9. Key observations include: (1) A single failure mechanism can contribute to

Table 6 | Summary of fault trees

BGI failure event	Retention ponds	Permeable pavements	Bioswales
No. of failure mechanisms	84	115	201
Basic events	53	90	82
Intermediate events	57	96	97
Top events	8	7	10

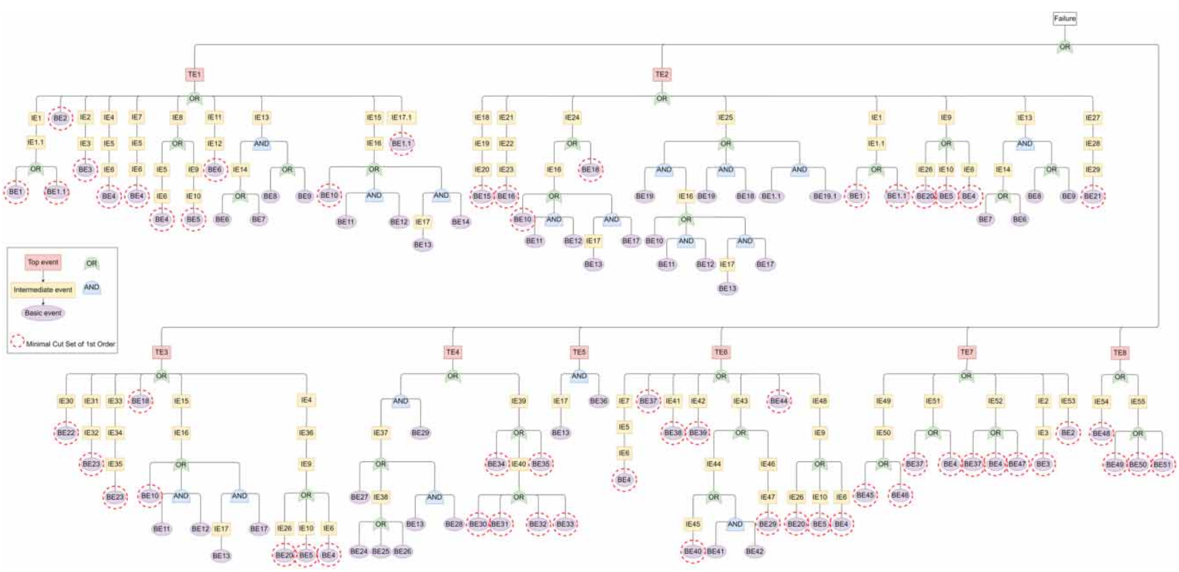


Figure 6 | Fault tree of retention ponds.

Table 7 | List of top events used in retention ponds' fault tree

Symbol	Top events	Symbol	Top events
TE1	Insufficient amenity value	TE5	Insufficient groundwater quality control
TE2	Insufficient runoff quality control	TE6	Insufficient safety value
TE3	Insufficient biodiversity value	TE7	Insufficient economic value
TE4	Insufficient runoff quantity control	TE8	Insufficient operational efficiency

Table 8 | List of intermediate events used in retention ponds' fault tree

Symbol	Intermediate events	Symbol	Intermediate events
IE1	Algal blooms	IE28	Insufficient retention time
IE1.1	Promote eutrophication	IE29	Hydraulic short-circuiting
IE2	Hiding the pond from public sight	IE30	Insufficient local species
IE3	Isolating the pond	IE31	Insects might be killed by light-induced exhaustion or predation by light-tolerant predators
IE4	Insufficient number of plant species and aquatic animals	IE32	Light attracts many insects
IE5	Creating anoxic conditions	IE33	Reducing or even eliminating foraging bats
IE6	Pool stratification	IE34	Isolating bat habitats from foraging grounds and exposing bats to visual predators like owls or cats
IE7	Invasive aquatic weeds	IE35	Loss of dark corridors and safe flight paths
IE8	Stink smell	IE36	Insufficient oxygen dissolved
IE9	Insufficient water circulation	IE37	Excess water
IE10	Creating dead zones	IE38	Hydraulic overloading
IE11	Damaging the natural morphology	IE39	Misalignment with upstream infrastructure
IE12	Frequent flood events	IE40	Elevation difference with the urban drainage system
IE13	Accumulating coarse sediments and floating oils	IE41	Encouraging direct access to open water
IE14	Polluted inflow	IE42	Impeding surveillance and rescue
IE15	Drought stress and habitat degradation	IE43	Structural damage
IE16	Permanent pool dried out	IE44	Possible landslides
IE17	Surface water infiltration	IE45	Layers of saturated subsoil do slip off the liner
IE17.1	Mosquito breeding	IE46	Scouring
IE18	Uncontrolled waste filling	IE47	Longer path of sheet flow
IE19	Carrying sediment, debris and waste materials from upstream areas	IE48	Accumulation of harmful substances
IE20	High velocity of surface runoff	IE49	Higher cost than expected
IE21	Premature mortality or loss of vigour of plants	IE50	More frequent maintenance
IE22	Preventing root penetration	IE51	Difficult inspection activities
IE23	Soil compaction	IE52	Low maintainability
IE24	No aquatic bench throughout the year	IE53	Reducing the performance as a community resource
IE25	Sediments resuspension	IE54	High maintenance requirements
IE26	Insufficient wind mixing	IE55	Underperformance and degradation
IE27	Reducing particles sedimentation		

multiple failure modes (e.g. BE4-IE7); (2) failure mechanisms may impact individual components, parts or the entire BGI system (e.g. IE14, IE43 and TE1); (3) different failure mechanisms can lead to different consequences for end users, ranging from merely reduced daily operational effectiveness to local flooding conditions (e.g. TE1-TE6); (4) some basic events are directly leading to immediate service failure (e.g. BE2-TE1), while others progress

Table 9 | List of basic events used in retention ponds' fault tree, along with their respective failure location and stage in BGI life cycle

Symbol	Basic events	Location	Phase
BE1	Soil is not amended before planting	Internal	Construction
BE1.1	Permanent pool depth less than 2 m	Internal	Design
BE2	The form, layout and planting are not designed and specified by landscape architects (only by engineers)	Internal	Design
BE3	High fence	Interface	Design
BE4	Permanent pool depth exceeding 2 m	Internal	Design
BE5	Layout including corners and sharp bends	Internal	Design
BE6	Connecting the pond with natural water bodies	Interface	Design
BE7	Inappropriate landscape design, e.g. highly vegetated, urban dirt accumulation zone	External	Design
BE8	Failed sediment forebay	Internal	Operation
BE9	Failed aquatic bench	Internal	Operation
BE10	Water losses by evapotranspiration are underestimated	Internal	Design
BE11	No sufficient water supply	External	Operation
BE12	Normal water losses by evapotranspiration	Internal	Operation
BE13	Allowed hydraulic connectivity with groundwater	Interface	Design
BE14	Groundwater deployment	External	Operation
BE15	The pond is situated on steep slopes	External	Design
BE16	Construction using heavy equipment	Internal	Construction
BE17	Depleted groundwater	External	Operation
BE18	No permanent pool	Internal	Design
BE19	Intermittent inflow	Interface	Operation
BE19.1	Wind mixing/inflow shear	External	Operation
BE20	Pond's length is not aligned with the direction of prevailing winds	Internal	Design
BE21	The ratio of flow path length to width is less than 3:1	Internal	Design
BE22	Over planting	Internal	Construction
BE23	Pond located next to artificial light sources	External	Design
BE24	Intense rainfall	External	Operation
BE25	Larger connected area than the design	Interface	Design
BE26	Deterioration of upstream infrastructure	External	Operation
BE27	Storage capacity is underestimated	Internal	Design
BE28	Groundwater flood	External	Operation
BE29	Failed emergency spillway	Internal	Operation
BE30	Designed levels and slopes are not accurately implemented	Internal	Construction
BE31	Soil subsidence	Internal	Operation
BE32	Compacted soil media	Internal	Operation
BE33	Flawed infrastructure pavement	Interface	Construction
BE34	Physical object blocking the inflow	Interface	Operation
BE35	Poor urban planning	Interface	Design
BE36	Surface water quality is less than groundwater quality	Interface	Operation
BE37	Slopes steeper than 1:3	Internal	Design
BE38	No safety bench around the pond	Internal	Design
BE39	Dense safety bench around the pond	Internal	Design
BE40	The requirements for benching are not implemented	Internal	Construction
BE41	Pond located on steep land	Internal	Design

(*Continued.*)

Table 9 | Continued

Symbol	Basic events	Location	Phase
BE42	Failed check dam	Internal	Operation
BE43	Failed emergency spillway close to the inlet	Internal	Operation
BE44	No consideration for the safe routing of floodwater and the embankment failure	Internal	Design
BE45	Highly contaminated runoff	External	Operation
BE46	Age of the system	Internal	Operation
BE47	Lack of routine inspection	Internal	Maintenance
BE48	Design is not adjusted to the available equipment and the usual management regime	Internal	Design
BE49	Lack of regular maintenance	Internal	Maintenance
BE50	Lack of occasional maintenance	Internal	Maintenance
BE51	Lack of remedial actions	Internal	Maintenance

through intermediate failure points (e.g. BE4-TE1) and (5) many failure mechanisms are complex and evolve, involving interconnected biological, physical, chemical or hydraulic processes (e.g. BE4-TE1). Furthermore, most critical failure mechanisms are relatively short and can directly propagate from the root cause towards the failure mode. For instance, no consideration for safe routing of floodwater and embankment failure in retention ponds leads directly to insufficient safety value. This emphasizes the importance of having backup measures and conducting frequent inspections.

The fault tree of retention ponds, Figure 6, shows that the majority of failure mechanisms of surface water treatment, amenity, biodiversity and safety are related to the condition of the permanent pool, highlighting its critical importance during the asset's life cycle to the overall performance. The fault tree of permeable pavements, Supplementary material, shows that decreasing the infiltration rate due to clogging is the predominant failure mechanism, primarily due to multiple contributing root causes. This underscores the critical importance of maintaining a reliable infiltration rate to ensure optimal performance, as well as the need for a well-maintained emergency overflow system to prevent urban flooding. The fault tree of bioswales, Supplementary material, shows that excess water caused by hydraulic overloading – when inflows exceed the designed infiltration, storage or conveyance capacity – and progressive declination of infiltration rate is the main failure mechanism. This finding highlights the importance of maintaining enough storage and conveys capacities along with an optimum infiltration rate. Additionally, the failure of water treatment due to uncontrolled hydraulic behaviour of surface water caused by uneven water distribution, high flow velocity, flow concentration and deep-water flow is another common functional failure in bioswales. This emphasizes the importance of regular filter basin inspection during operation.

(1) A root cause (shown as basic event) can be either a sudden- or a time-dependent event (e.g. BE42 and BE22) triggered by human intervention (e.g. BE35) or developed by nature (e.g. BE12); (2) a single root cause (e.g. BE4) can initiate multiple failure mechanisms and (3) a root cause (as shown in Table 9 and Figure 6) can arise at any stage of the BGI life cycle and could be a component failure, an external event or a wrong integration with an urban environment.

Most root causes (see Figure 7) originate from the BGI itself: 56% for permeable pavements and 63% for retention ponds and bioswales. External environmental factors account for a significant share in permeable pavements (36%), but play a lesser role in retention ponds (19%) and bioswales (24%). In contrast, poor integration with the urban drainage system initiates comparatively fewer root causes: 9% in permeable pavements, 17% in retention ponds and 12% in bioswales.

When broken down by the life cycle phase, root causes for retention ponds and bioswales predominantly emerge during the design phase (44 and 46%, respectively), such as inadequate sizing or poor inlet/outlet placement. For permeable pavements, however, operational and construction-related factors dominate, accounting for 46 and 24% of the root causes, respectively. Operational issues often include clogging due to sediment accumulation and inadequate maintenance, while construction-related problems often involve errors such as improper base layer installation or aggregate layers compaction during installation. Root causes linked to maintenance represent less than 10% across all systems and are typically associated with economic inefficiencies rather than

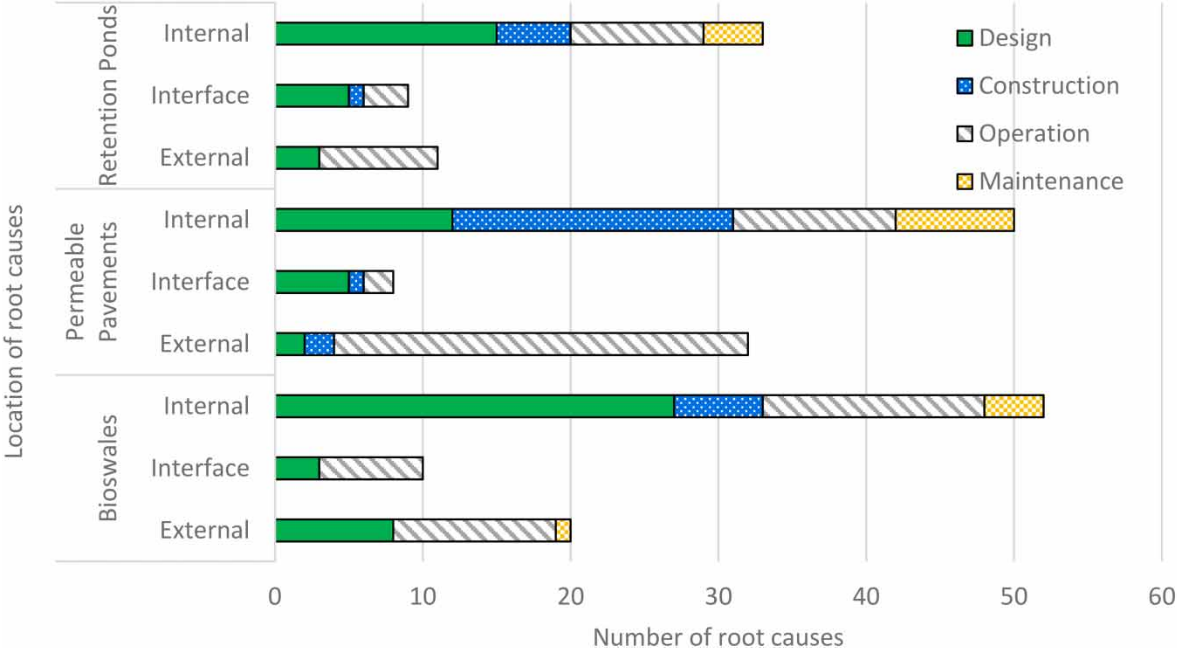


Figure 7 | Number and location of root causes per BGI's life cycle.

immediate system failure. These findings highlight two key insights: First, BGI systems are highly sensitive to internal design and construction decisions. Second, the dynamic interaction with the surrounding urban environment plays a substantial role in performance outcomes.

Many of the reported root causes in Figure 6 are first-order MCSs and can alone cause system failure, revealing the inherent vulnerability of BGI systems to single-event failure.

The results in Figure 8 show that each BGI system tends to be particularly sensitive to a distinct category of critical MCSs. For instance, root causes related to design are the most critical MCSs to retention ponds' failure as follows: BE4: Permanent pool depth exceeding 2 m, BE5: Layout including corners and sharp bends and BE20: Pond's length is not aligned with the direction of prevailing winds. These findings underscore the importance of customizing retention ponds' design to the contextual site. For permeable pavements, the most critical MCSs are associated with operational factors, including BE9: High traffic load, BE89: Low hydraulic performance and BE8: Weight of the applied soil. This underlines the need for robust operational controls and load-bearing designs to ensure long-term system function. In bioswales, the most critical MCSs are associated with vegetation layer conditions, as follows: BE7: Frequent pedestrian traffic, BE14: Invasive weeds and plants and BE15: Wrong type of vegetation. This emphasizes the importance of frequent monitoring of vegetation health to avoid operational failures or disruptions.

Notably, the critical root causes are effectively contributing to multiple failure modes. For instance, a permanent pool with depth exceeding 2 m leads to insufficient amenity, biodiversity, safety and economic values, and less runoff quality control.

The results enable tracing failure chains, identifying vulnerable components and pinpointing sensitive parameters to system failure, which can be employed to design effective field inspections that capture early signs of failure.

As shown in Figure 6, many failure mechanisms are partially shared between different BGI systems that belong to the same typology, indicating the possibility of grouping fault trees and simplifying the field. Nevertheless, special attention must be paid to the uniqueness and the contextual location of each case. For example, the root causes and intermediate failure points that initiate top-layer clogging of bioswales are the same as those in permeable pavements. However, a unique failure mechanism arises in permeable pavements, triggered by allowed traffic. Therefore, another approach worth investigating is to analyse the failure mechanisms of BGI based on the components' functionality rather than the asset as a whole.

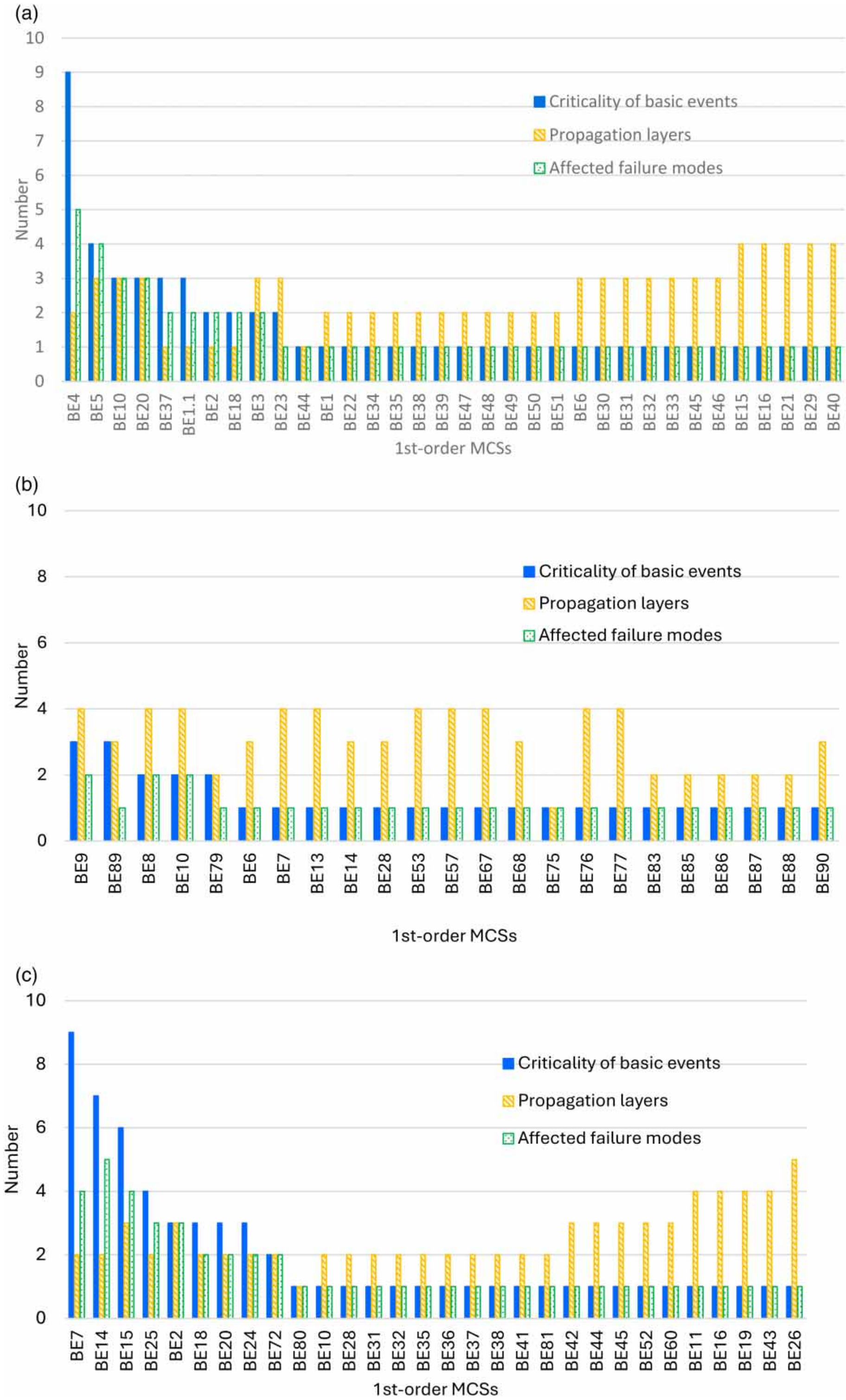


Figure 8 | Criticality, propagation layers and affected failure modes of first-order MCSs for (a) retention ponds, (b) permeable pavements and (c) bioswales.

4. CONCLUSIONS

In the Netherlands, BGI systems are increasingly replacing traditional adaptation strategies due to their sustainability and multifunctional benefits. However, these systems are often not well-maintained after initial installation, leading to their underperformance or operational failure. This paper aimed to identify the potential failure mechanisms of permeable pavements, bioswales and retention ponds across their life cycle and in dynamic interaction with the urban environment. Various types of literature were reviewed in combination with experts' assessment to identify as many failure mechanisms as possible. FTA was used to map root causes of different failures to ultimate events impacting end users, all via different cause-and-effect type failure mechanisms. The first-order MCSs were identified and prioritized based on their criticality, propagation path and number of affected failure modes. The results were validated in a discussion and online survey with experts. Three detailed fault trees were developed for the three analysed BGI systems, incorporating a total of 225 basic events, 250 intermediate events and 25 failure modes.

The results indicate that all components of BGI are susceptible to failure. Clogging and hydraulic overloading are identified as dominant failure mechanisms in permeable pavements and bioswales. Failure of water treatment due to uncontrolled hydraulic behaviour of surface water is another common functional failure in bioswales. The permanent pool was found to be the most critical component that significantly influences the overall performance of retention ponds. Each BGI system seems to be particularly vulnerable to a specific category: retention ponds are vulnerable to design parameters, permeable pavements to operational factors and bioswales to vegetation conditions.

Future work should expand the analysis to include additional potential failure mechanisms arising under different operational environments, thereby supporting the replication and generalization of the study across countries. In addition, the findings should be validated through engagement with a wider panel of experts and benchmarked against operational records from utilities currently managing BGI.

In addition to the above, the results underscore the necessity of improving the current asset management practices to address the complexity, diversity and uniqueness of BGI. Key recommendations include:

- Improve definitions of failure thresholds to minimize uncertainty and frame the discussion with the stakeholders.
- Develop more detailed documentation regarding the BGI designs, construction processes and sequences, operational performance, maintenance activities, handling of citizen complaints and the surrounding environmental factors.
- Design a standardized and effective inspection and monitoring protocol that clearly defines inspection items, measurable performance indicators, inspection frequency, required tools and responsible personnel to capture early signs of failures.
- Ongoing improvement of BGI standards and practices using feedback loops and performance outcomes.

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AUTHOR CONTRIBUTIONS

O.A.: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. B.R.: Validation, Writing – review & editing. M.B.: Validation, Writing – review & editing. E.G.: Validation, Writing – review & editing. Z.K.: Conceptualization, Supervision, Writing – review & editing. J.G.L.: Funding acquisition, Conceptualization, Supervision, Validation, Writing – review & editing.

DATA AVAILABILITY STATEMENT

All relevant data are available from https://doi.org/10.4121/9249fd11-7115-4485-80ab-97fb911bcffa.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Auger, S., Besnier, J.-B., van Bijnen, M., Cherqui, F., Chuzeville, G., Clemens-Meyer, F., Jaatun, M. G., Langeveld, J., Le Gat, Y., Moin, S., van Oosterom, G. E., van Riel, W., Roghani, B., Rokstad, M. M., Røstum, J., Tscheikner-Gratl, F. & Ugarelli, R. (2024) Chapter 8: Data management and quality control. In: Cherqui, F., Clemens-Meyer, F., Tscheikner-Gratl, F. & v. Duin, B. (eds.) *Asset Management of Urban Drainage Systems*. London: IWA Publishing Unit, pp. 299–342.

Bahrami, M., Roghani, B., Tscheikner-Gratl, F. & Rokstad, M. M. (2024) A deep dive into green infrastructure failures using fault tree analysis, *Water Research*, **257**, 121676. doi:10.1016/j.watres.2024.121676.

Barraud, S., Bosco, E., Clemens-Meyer, F. H. L. R., Fernandes, G., Le Gat, Y., de Haan, R. A., Luimes, R. A., Makris, K., Rooyackers, F. A. M., Scheperboer, I. C., Skjelde, J. & Suiker, A. S. J. (2024) Chapter 5: Deterioration processes and modelling in urban drainage systems. In: Cherqui, F., Clemens-Meyer, F., Tscheikner-Gratl, F. & v. Duin, B. (eds.) *Asset Management of Urban Drainage Systems*. London: IWA Publishing, pp. 131–230.

Barsalou, M. A. (2014) *Root Cause Analysis: A Step-by-Step Guide to Using the Right Tool at the Right Time*. Portland: CRC Press.

Blecken, G.-T., Hunt, W. F., Al-Rubae, A. M., Viklander, M. & Lord, W. G. (2017) Stormwater control measure (SCM) maintenance considerations to ensure designed functionality, *Urban Water Journal*, **14** (3), 278–290. doi:10.1080/1573062X.2015.1111913.

Boogaard, F., Lucke, T., Giesen, N. v. d. & Ven, F. v. d. (2014) Evaluating the infiltration performance of eight Dutch permeable pavements using a new full-scale infiltration testing method, *Water*, **6**, 2070–2083. doi:10.3390/w6072070.

Brolsma, R., Rooze, D. & Boogaard, F. (2022) *Factsheet: waterpasserende, waterdoorlatende en doorgroeibare verhardingen 2022 (Fact Sheet: Water-Passing, Permeable and Growable Pavements 2022)*. s.l: Regio Deal Bodemdaling Groene Hart.

Cherqui, F., Clemens-Meyer, F., Duin, B. v. & Tscheikner-Gratl, F. (2024) Introduction to urban drainage asset management: if something exciting happens, we've done it wrong! In: Cherqui, F., Clemens-Meyer, F., Tscheikner-Gratl, F. & v. Duin, B. (eds.) *Asset Management of Urban Drainage Systems*. London: IWA Publishing, pp. 1–18.

CoP (2022) *Handreiking Waterinfiltrerende Verhardingen (Guidelines for Water-Infiltrating Pavements)*. Utrecht: Community of Practice Waterinfiltrerende Verhardingen.

CROW (2019) *Analyse klimaatadaptatieprojecten ten behoeve van aanpassing richtlijnen (Analysis of Climate Adaptation Projects for the Purpose of Adjusting Guidelines)*. s.l: CROW Knowledge Module.

CROW (2023) *Kwaliteitcatalogus openbare ruimte 2023 (Quality Catalogue for Public Space 2023)*. Utrecht: CROW.

CROW (2025) *De RAW-systematiek: stelsel juridische, administratieve en technische voorwaarden voor GWW-bestekken (The RAW System: System of Legal, Administrative and Technical Conditions for Civil Engineering Specifications)*. Ede: CROW.

CROW (n.d.) *CROW online kennisbank (CROW Online Knowledge Bank)*. Ede, Netherlands: CROW (Kennisplatform CROW). Available at: https://kennisbank.crow.nl/kennismodule (Accessed: 16th April 2025).

DelGrosso, Z. L. (2018) *Identifying Key Factors for the Implementation and Maintenance of Green Stormwater Infrastructure. Master's thesis*, Virginia Polytechnic Institute and State University, Blacksburg.

Elsevier (2025) *Scopus*. Available at: https://www.scopus.com/pages/home?display=basic#basic (Accessed: 1st November 2025).

Erickson, A. J., Weiss, P. T. & Gulliver, J. S. (2013) *Optimizing Stormwater Treatment Practices: A Handbook of Assessment and Maintenance*. s.l: Springer New York.

Ertl, T., Kearney, K., Funke, F., Reinstaller, S., Kleidorfer, M. & Muschalla, D. (2024a) *Niederschlagswasserbehandlung jenseits originärer Bemessungsereignisse und planmäßiger Betriebszustände (Rainwater Treatment Beyond Original Design Events and Planned Operating Conditions)*. Vienna: Federal Ministry of Agriculture, Forestry, Regions and Water Management.

Ertl, T., Kearney, K., Funke, F., Reinstaller, S., Kleidorfer, M. & Muschalla, D. (2024b) *Leitfaden zum Umgang mit Störfällen und außerordentlichen Ereignissen in der städtischen Niederschlagswasser bewirtschaftung (Guideline for Dealing with Incidents and Extraordinary Events in Urban Rainwater Management)*. Vienna: Bundesministerium für Land- und Forstwirtschaft, Regionen und Wasserwirtschaft.

European NWRM+ Platform (2013) *Benefit Tables*. Available at: https://www.nwrm.eu/catalogue-nwrm/benefit-tables (Accessed: 07th March 2025).

Gemeente Amsterdam (2024) *Handboek Rood: standaard voor het Amsterdamse straatbeeld (Handbook Red: Standard for the Amsterdam Streetscape)*. Amsterdam: Gemeente Amsterdam.

Hau, H.-M., Langevoort, M., Leusink, E., Schoonderbeek, J., Stamsnijder, E., Veldkamp, T. & Wentink, R. (2024) *Richtlijnen voor locatie- en systeemkeuze, ontwerp, aanleg en beheer van infiltratievoorzieningen (Guidelines for Location and System Selection, Design, Construction, and Management of Infiltration Facilities)*. s.l: Stichting RIONED en STOWA.

Hirschman, D. J. & Woodworth, L. (2010) *Design, Construction, and Maintenance of LID Practices: Results From a Field Assessment in Virginia's James River Watershed*. San Francisco: American Society of Civil Engineers, pp. 1075–1088.

Hout, G. v. d. (2024) *Waterpasserende Verharding: overzicht onderzoeken naar functioneren, beheer & onderhoud (Water-Passing Pavement: Overview of Research into Performance, Management & Maintenance)*. Rotterdam: IBR Stedelijk Water en Geotechniek.

Kavehei, E., Chudal, B., Carlson, D., Rabbidge, J., Herath, S., Pearce, A., Coutinho, A. & Kinsey, C. (2023) 'Assessing the condition of bioretention basins; investigating influential factors on asset performance', *HWRS2023: Hydrology & Water Resources Symposium, Sydney*.

Langeveld, J. G., Cherqui, F., Tscheikner-Gratl, F., Muthanna, T. M., Fernandez-Delgado Juarez, M., Leitão, J. P., Roghani, B., Kerres, K., Almeida, M. C., Werey, C. & Rulleau, B. (2022) Asset management for blue-green infrastructures: a scoping review, *Blue-Green Systems*, **4** (2), 272–290. doi:10.2166/bgs.2022.019.
Leskens, A. & Lekkerkerk, J. (2020) *De Infiltrerende Stad 1: systeemanalyse (The Infiltration City 1: System Analyses)*. Rotterdam: Hogeschool Rotterdam.
Meijs, S., Arbouw, G., de Graaff, R., van Helden-Solleveld, T., Helmer, M., van Hemert, P., Hoorn, M., van Nieuwaal, K., Schoute, E., Thijssen, M., Westera, H. & van Zeggeren, B. (2018) *National Climate Adaptation Strategy (NAS) of the Netherlands: Implementation Programme 2018–2019*. The Hague: Ministry of Infrastructure and Water Management.
Nieuwenhuis, E. M. (2023) *The End of the Sectoral Approach? Understanding the Role of Integration in Urban Water Management*. *Thesis*. Delft University of Technology, Delft.
O'Donnell, E. C., Thorne, C. R., Yeakley, J. A. & Chan, F. K. S. (2020) Sustainable flood risk and stormwater management in blue-green cities; an interdisciplinary case study in Portland, Oregon, *Journal of the American Water Resources Association*, **56** (5), 757–775. doi:10.1111/1752-1688.12854.
Pan, K., Liu, H., Gou, X., Huang, R., Ye, D., Wang, H., Glowacz, A. & Kong, J. (2022) Towards a systematic description of fault tree analysis studies using informetric mapping, *Sustainability*, **14**, 11430. doi:10.3390/su141811430.
Radfar, A. & Rockaway, T. D. (2016) Clogging prediction of permeable pavement, *Journal of Irrigation and Drainage Engineering*, **142** (4), 04015069. doi:10.1061/(ASCE)IR.1943-4774.0000975.
Razzaghmanesh, M. & Beecham, S. (2018) A review of permeable pavement clogging investigations and recommended maintenance regimes, *Water*, **10** (3), 337. doi:10.3390/w10030337.
RIONED (2019) *Infiltratende verharding (Infiltrating Pavement)*. Ede, Netherlands: Stichting RIONED. Available at: https://www.riool.net/kennisbank/onderzoek/modelleren-hydraulisch-functioneren/stap-v-benodigde-gegevens-inventariseren/oppervlakken-inventariseren/infiltrerende-verharding (Accessed: 26th May 2025).
Roghani, B., Bahrami, M., Cherqui, F., Tscheikner-Gratl, F. & Rokstad, M. M. (2025) Exploring key characteristics of performance indicators for green infrastructure assessment, *Science of The Total Environment*, **969**, 178819. doi:10.1016/j.scitotenv.2025.178819.
Rombout, J., Boogaard, F., Kluck, J. & Wentink, R. (2007) *Zuiverende Voorzieningen Regenwater (Purifying Rainwater Facilities)*. Utrecht: STOWA.
Stichting RIONED (n.d.) *Kennisbank stedelijk water (Urban Water Knowledge Bank)*. Available at: https://www.riool.net/kennisbank (Accessed: 15th April 2025).
Tang, Y.-T., Chan, F. K. S., O'Donnell, E. C., Griffiths, J., Lau, L., Higgitt, D. L. & Thorne, C. R. (2018) Aligning ancient and modern approaches to sustainable urban water management in China: Ningbo as a 'Blue-Green city' in the 'Sponge city' campaign, *Flood Risk Management*, **11** (4), e12451. doi:10.1111/jfr3.12451.
Utrecht Municipality (2021) *Handboek Openbare Ruimte (Public Space Handbook)*. Utrecht: s.n.
Veldkamp, T., Shoemaker, T. & Klück, J. (2020) *WP2: functioneren van Infiltrerende Verharding in de Praktijk (WP2: Functioning of Infiltrating Pavement in Practice)*. s.l: Hogeschool Amsterdam.
Veldkamp, T. I. E., Boogaard, F. C. & Kluck, J. (2022) Unlocking the potential of permeable pavements in practice: a large-scale field study of performance factors of permeable pavements in the Netherlands, *Water*, **14**, 13.
Vollaers, V., Nieuwenhuis, E., Ven, F. v. d. & Langeveld, J. (2021) Root causes of failures in sustainable urban drainage systems (SUDS): an exploratory study in 11 municipalities in the Netherlands, *Blue-Green Systems*, **3** (1), 31–48. doi:10.2166/bgs.2021.002.
Woods Ballard, B., Wilson, S., Udale-Clarke, H., Illman, S., Scott, T., Ashley, R. & Kellagher, R. (2015) *The SuDS Manual*, 6th edn. London, UK: CIRIA.
Zabicki, S. (2018) *A Study on the Failure Mechanism of Permeable Pavement Surfaces*. *Master's thesis*, Utrecht University, Utrecht.

First received 5 November 2025; accepted in revised form 3 February 2026. Available online 13 February 2026