Water Research 257 (2024) 121676

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

A deep dive into green infrastructure failures using fault tree analysis

Mahdi Bahrami *, Bardia Roghani, Franz Tscheikner-Gratl, Marius Møller Rokstad

Norwegian University of Science and Technology (NTNU), Department of Civil and Environmental Engineering, Water and Wastewater Engineering (VA) Group, Trondheim, Norway

A R T I C L E I N F O

Keywords:
Data collection
Asset management
Component failure
Proactive maintenance
Risk assessment
Nature-based solutions

A B S T R A C T

Green Infrastructure has transformed traditional urban stormwater management systems by fostering a wide range of service functions. Despite their popularity, green infrastructure's performance can deteriorate over their lifecycle, leading to operational failures. The operation of green infrastructure has predominantly relied on reactive maintenance strategies. To anticipate malfunctions and enhance the performance of green infrastructure in the long run, failure data needs to be recorded so that deterioration processes and component vulnerabilities can be recognized, modelled and included in predictive maintenance schemes. This study investigates possible failures in representative GIs and provides insights into the most important events that should be prioritized in the data collection process. A method for qualitative Fault Tree Analysis using minimal cut sets are introduced, aiming to identify potential failures with the minimum number of events. To identify events of interest fault trees were constructed for bioswales, rain gardens and green roofs, for three groups of service function failures, namely runoff quantity control, runoff quality control and additional service functions. The resulting fault trees consisted of 45 intermediate and 54 basic events. The minimal cut set analysis identified recurring basic events that could affect operation among all three green infrastructure instances. These events are 'trash accumulation', 'clogging due to sediment accumulation', and 'overly dense vegetation'. Among all the possible cut sets, events such as 'plants not thriving', 'invasive plants taking over', and 'deterioration caused by external influences' could potentially disrupt most of the service functions green infrastructure provides. Furthermore, the analysis of interactions between component failures shows vegetation and filter media layer failures have the highest influence over other components. The constructed fault trees and identified basic events could be potentially employed for additional research on data collection processes and calculating the failure rates of green infrastructure and as a result, contribute to a shift toward their proactive operation and maintenance.

1. Introduction

Urbanization and climate change have resulted in an increase in extreme rainfall events and significant changes to catchment hydrologic responses (Ahiablame et al., 2012; Fletcher et al., 2013). Traditional urban stormwater management systems, as the so-called "grey" infrastructure is often not able to cope with those changes as it was designed based on historical rainfall data and guidelines, while upsizing the current stormwater pipes seems unrealistic as it may require expensive and disruptive projects and may even exacerbate flooding issues (e.g. backwater effects or increase in peak flows in the outlet) (Moore et al., 2016). Short-duration rainfall events over Northern Europe have intensified due to climate change, occurring more frequently in cold months (Fowler et al., 2021). As such, the risk of overflow in combined sewer systems increases. Due to the limited capacities of downstream treatment plants, there's a higher chance of excess untreated wastewater and runoff being discharged into recipient water bodies. Also, the increase in impervious surfaces in urban areas has led to extreme stormwater runoff, which causes flooding, property damage, and detrimental health impacts for the public, as stormwater often contains pollutants from street surfaces or the air (Butler et al., 2018). In contrast, modern approaches view stormwater as a ``resource'' that can provide social, environmental, and economic benefits. An example of this is the three-stage approach to stormwater management in Norway, where the first stage concerns everyday events that should be infiltrated locally (Skrede et al., 2020). In this regard, (semi) natural control measures have been introduced as a way to facilitate water retention and infiltration, reduce pressure on grey infrastructure, and complement traditional systems (Berland et al., 2017). According to Fletcher et al. (2014) proposed solutions are often named differently based on level of focus and specificity of techniques and principles. To address the broad range

* Corresponding author.
E-mail address: mahdi.bahrami@ntnu.no (M. Bahrami).

https://doi.org/10.1016/j.watres.2024.121676
Received 4 December 2023; Received in revised form 29 March 2024; Accepted 23 April 2024
Available online 24 April 2024

Abbreviations

GI	green Infrastructure
FTA	fault tree analysis
MCS	minimal cut sets
TE	top event
IE	intermediate event
BE	basic event

of services and co-benefits provided by these solutions, and for the sake of consistency, Green Infrastructure (GI), which is the most frequent used keyword in this regard (Caparrós-Martínez et al., 2020), is the adopted term in this paper hereafter. Furthermore, to address the various dimensions and services provided by GIs, the term 'service functions' will be used throughout this paper (Roghani et al., 2023). GI encompasses a variety of types, such as swales, rain gardens, and green roofs. These installations serve multiple purposes including reducing flood risk, preserving the environment, improving aesthetics, and enabling a more circular usage of stormwater by managing the stormwater near its source and mimicking pre-urban hydrologic processes, such as natural retention, infiltration, and evapotranspiration (Butler et al., 2018). The elements constituting GIs, such as vegetation covers, soil textures, and other components, effectively contribute to minimizing runoff velocities, prolonging concentration times, and treating pollutants in stormwater (Moura et al., 2016).

While GIs can be sustainable solutions for urban water management, their effectiveness can fluctuate based on their type, combination, placement, and condition over their lifecycle. Individual GI measures are mainly capable of mitigating local rainfall events in small areas, while studies have shown combinations of GI and grey infrastructure in larger catchments can interact to handle medium events by delaying flood peaks and subsequent runoff (Bahrami et al., 2019; Jia et al., 2022; Wang et al., 2023; Wu et al., 2023). This cumulative effect is also visible for ecosystem services provided by GIs such as biodiversity enhancement and urban heat mitigation (European Commission, 2021). However, GIs are prone to deterioration and failure, as any other infrastructure. Up until now, research has focused on their design (Wagner et al., 2023), stationary and non-stationary modelling (Mohsen Hassan Abdalla et al., 2022; Pons et al., 2023), urban planning (Fu et al., 2021), co-benefits (Le Coent et al., 2021), performance at the time of commissioning (Shahzad et al., 2022; Ghodsi et al., 2023), and performance assessment and monitoring (Ding et al., 2023; Roghani et al., 2023). However, questions remain regarding their long term performance, maintenance and cost-effectiveness compared to grey infrastructure of the same capacity (Langeveld et al., 2022). For instance, high uncertainties in efficiency of bioretention systems over their life cycle could result in overestimating of the actual performance (Wang et al., 2021). In addition, allocating suitable funding for implementing and maintaining green initiatives in cities is a key issue for municipal administrations (Hansen et al., 2015; Kabisch et al., 2015). Therefore, any efforts that support their long-term operation are valuable and should be incorporated into GI programs.

Limited research has been conducted on how the operation of GI assets affects their performance over time, however, some studies indicate that their performance deteriorates. Gonzalez-Merchan et al. (2012) studied the hydraulic performance of an infiltration basin over a course of 7 years and found high variabilities of hydraulic performance between different events. The results show clogging takes place progressively and can be affected by vegetation growth. Drake and Bradford (2013) studied the surface permeability of permeable pavements after maintenance and found large variations in the post-treatment infiltration rates. Moreover, GIs can be a source of stormwater pollution, which can arise from conflicting demands (e.g., stormwater retention vs. landscaping), deterioration of components, maintenance problems and outdated designs (Müller et al., 2020). Vegetated GIs may leach harmful chemicals into stormwater (Kondo et al., 2016; Flanagan et al., 2019), significantly increase Total Suspended Solids (TSS) concentrations (Winston et al., 2016), or act as secondary sources of pollution, i.e. re-releasing pollutants originating from other sources (Kondo et al., 2016; Müller et al., 2020). Ensuring their long-term performance aligning with the initial design intent requires suitable monitoring, at the right place and right time, to proactively intervene before malfunctions occur (Cherqui et al., 2019a).

Operation and maintenance of GIs is a context-specific problem that depends on several factors such as local climate conditions and human resources. The variety of different types, structural compositions, and sizes of GI also makes them more difficult to manage, requiring different monitoring schemes and practices to be applied to each instance (Langeveld et al., 2022). Due to a lack of resources and supervisory schemes in the majority of the cases, only the most critical GIs are monitored. Langeveld et al. (2022) investigated the current state of GI operation and discussed five preconditions for effective asset management. One of those pre-conditions is sufficient information about the system and its environment. This is a basic requirement for any asset management approach beyond "run to fail", but difficult to obtain for GIs. Quantitative measurements of performance are mainly carried out for research purposes and often based on assumptions of perfectly operational GIs.

The traditional GI asset management approach has predominantly relied on reactive maintenance practices, addressing failures and issues after they occur (Cherqui et al., 2019a; Langeveld et al., 2022). However, with the increasing importance of GIs in urban environments, there is a growing recognition of the need to shift towards proactive maintenance methods (Cossais et al., 2017; Cherqui et al., 2019a; Langeveld et al., 2022). This paradigm shift emphasizes the significance of identifying potential failure points/mechanisms and implementing preemptive measures to ensure the optimal performance and longevity of GI systems. Information on the current structural condition of individual GIs, combined with a good understanding of service function failures and deterioration models, can greatly enhance the ability of asset owners to manage GIs in a cost-effective manner (Vollaers et al., 2021). Data collection and monitoring methods can be used to identify and describe processes that might prevent assets maintaining their performance to the desired level, and furthermore to determine appropriate ways to eliminate or control them (Alegre and Coelho, 2012).

As the understanding of GI failures continues to evolve, a notable gap persists in terms of collecting operational data on failures within GI systems (Cherqui et al., 2019b). Previous studies have primarily focused on specific failures such as clogging or hydraulic performance deterioration within controlled experimental settings. Some researchers have explored a broader range of failures, such as Silva et al. (2015), who surveyed green roofs in Portugal, identifying anomalies and proposing maintenance plans, and Thurston (2017), who established operational definitions for green roof failures. However, these studies also revealed that stakeholders often lacked sufficient information and preparation to address the technical complexities of GI maintenance. Other researchers such as Blecken et al. (2015) have addressed common causes of failure and highlighted crucial maintenance requirements for various GI types, while Delgrosso et al. (2019) analyzed GI maintenance programs in the US, specifically in Fairfax County, Virginia, and found that deficiencies in such programs varied based on ownership (public or private GI), site conditions, and frequency of routine maintenance. Furthermore, the current post-construction inspection program was found to be failing in detecting GI failures. The study suggested thorough recording of construction and postconstruction inspection items to improve GI longevity and future decision making regardings. In a more comprehensive analysis, Vollaers et al. (2021) investigated the root causes of failures throughout the design, construction, and maintenance phases of GIs. The study highlights the interface between GIs and other urban infrastructure as the prominent failure location, while the underlying causes of failures are detected to be socio-institutional in nature.

One effective method to systematically study interdependencies between potential failure events in complex systems is Fault Tree Analysis (FTA) (Sadiq et al., 2008; ten Veldhuis et al., 2011). FTA is typically discussed at the operational levels of asset management of water and wastewater utilities, since this level focuses on developing and executing short-term plans and measures for a group of components that are vital to the operation of the asset. The primary goal is to enhance the asset's operation by providing necessary support. At the operational level, FTA can be used to guide decision-making about maintenance activities, as well as monitoring and inspection planning (Alegre and Coelho, 2012; Pérez and Ugarelli, 2014). However, the utilization of FTA extends beyond the operational levels of asset management within water and wastewater utilities (ten Veldhuis et al., 2011; Lindhe et al., 2012; Aghapoor Khameneh et al., 2019; Spalanzani et al., 2020; Viñas et al., 2022).

To address the gap regarding GI failure data, this study presents a systematic approach for failure detection, classification, and determination of underlying causes using FTA. The objective is to establish a thorough examination of failures, aiming to achieve a comprehensive understanding of the cause-and-effect relationships between GI components and service function failures and their associated basic/intermediate events. Because of its simplicity and similarity to binary logic analysis, FTA has advantages over other methods which require mathematical equations and impose complex analysis for large systems (Aliee and Zarandi, 2013). The significance of this point becomes even more pronounced in the case of GIs, where scant data exists regarding their diverse failure modes and the factors influencing their occurrence. Consequently, this paper presents a method for FTA construction for GIs based on component roles. The practical implications of this methodology are then investigated by applying it to three types of highly adapted GIs. Furthermore, cut sets which are combinations of events that result in the occurrence of the top event (Ren et al., 2017), are used to pinpoint vulnerable components (Beresh et al., 2008), aiding in prioritization and the allocation of resources for data collection.

2. Methodology

In this study, a detailed methodology for creating fault trees for GIs is presented. The approach is based on established methods for FTA, adapted from previous studies such as Masalegooyan et al. (2022) and Ong et al. (2022) and inspection and maintenance guidelines. An overview of methodology applied in this study is illustrated in Fig. 1. Afterwards, the outcomes of each step are elaborated upon in the ensuing results section.

2.1. *Define study boundaries*

To effectively employ the FTA method, it is essential to establish clear boundaries of the system under analysis and define the scope (Beresh et al., 2008). The establishment of these boundaries is guided by the objectives and focus of the analysis, ensuring a clear and targeted approach to the assessment. Boundary conditions play a pivotal role in determining the specific components of the system, such as a particular type (or element) of GI that will be included or excluded from the analysis, or definitions of their failures. For example, some green roofs may only contain essential elements (e.g., waterproofing membrane or root barrier) and serve solely to capture and retain stormwater, while others may additionally include features such as recreational spaces (e. g., incorporating seating areas). Moreover, it is important to clarify what would be the scale at which failures are investigated (For example at the scale of an individual GI instead of looking at the whole network of GIs throughout the urban environment).

2.2. *Identify common GI components*

In the present study, FTA is applied considering GI components and their respective roles in relation to GI service functions. It is necessary to develop an understanding of the intricacies of GI design, while dealing with such complexity. For instance, GIs could potentially improve biodiversity in urban environments, which is mainly possible due to the existence of vegetation. Furthermore, it's important to note that GI components frequently exhibit interdependencies, not only among themselves but also with their surrounding environment. For instance, the condition of the soil and the amount of sunlight during the year can have a significant impact on the health of the vegetation. For this reason, common designs and components of GIs need to be extracted in order to construct fault trees that represent their failures by incorporating the

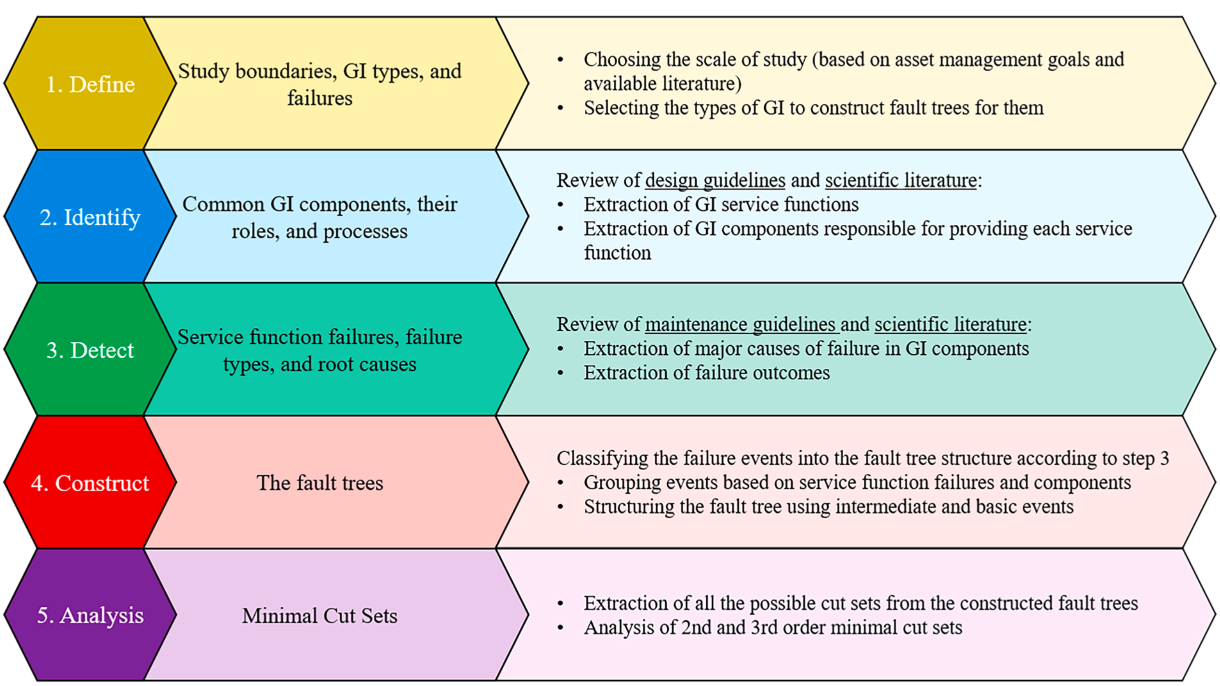

Fig. 1. Overview of research methodology, with numbers corresponding to each subsection in methodology and results.

widely employed elements. In this study, publicly available design guidelines and scientific literature addressing GI service functions and components were reviewed. The search was conducted by combining GI names such as 'green roofs', 'bioswales', and 'rain gardens' with terms such as 'design guideline', 'benefits', and 'components'. A broad range of literature from around the world addressing different climate conditions and design criteria for GIs were gathered. Table 1 presents the complete list of literature used in this stage, including details on the type of extracted information from each reference. Components were extracted and classified based on their role in providing different service functions. For more detail, readers are encouraged to check Appendix I.

2.3. Detect GI service function failures and causes

After specifying component roles, scientific literature discussing GI maintenance considerations and failures, along with inspection and maintenance guidelines, fact sheets, and inspection forms were gathered, similar to the search process described in the last step (see the last column in Table 1). The literature were reviewed to investigate underlying causes of failure in each component. This information is provided in maintenance guidelines in the form of instructions that further explains the root causes of the problem. For instance, statements such as 'Sediment accumulating at the overflow outlet could impair its drainage function and cause surface ponding and vegetation die-off' from Toronto and Region Conservation Authority (TRCA) (2016) were used to cross reference an event such as sediment accumulation to a function such as 'drainage'. For more detail, readers are encouraged to check Appendix I. Furthermore, the effect of one component failure on other components was investigated in the same manner. The interactions between component failures may affect the asset's performance, inhibiting it from performing said roles. For example, a check dam is used in swales to slow the flow rate and buy time for infiltration; but ponding for extended periods of time (beyond 48 h) can have adverse effects on vegetation health.

2.4. Constructing the fault trees

FTA is a logical and diagrammatic tool used to assess the probability or likelihood of a final undesired event occurring based on the occurrence or non-occurrence of other events (Yazdi et al., 2023). Depending on the information available and the goals of the analysis, FTA may be qualitative, quantitative, or both (Kabir, 2017; Yazdi et al., 2019). The tree formation for FTA starts with defining the Top Event (TE), which is the primary event of concern or undesired state that is the focus of the analysis, and identifying the contributing Intermediate Events (IE) that have the potential to lead to the occurrence of the TE. The process continues until all the basic causes of the TE are identified. If an event cannot be further expanded or described, it is considered as a Basic Event (BE). FTA is a binary analysis method, which means BE and IE events can either happen or not. The basic and intermediate events are connected through logical AND/OR gates. AND gates represent scenarios where multiple events must occur simultaneously for an output failure event to happen (i.e. the output is true only when both inputs are true), while OR gates signify that the failure event can result from any one of the contributing events occurring independently (i.e. the output is true if one or both of the inputs are true.) (Beresh et al., 2008). For example, TSS pollution in outflow from a bioswale could happen because of sediment buildup AND loss of vegetation. On the other hand, an inlet not directing water inside a rain garden (IE) could be caused by trash OR sediment accumulating inside of the component. In addition, when a single fault tree becomes too large, Transfer gates are used to separate the sub-branches of a specific section of the tree and illustrate them individually.

In this study, the TE is the failure of GI in delivering one of its designated service functions. In order to structure the fault trees in a practical way that conveys the cause-effect relationships clearly, we

Table 1
List of literature reviewed in this study to extract information on GI components, GI service functions, and failure events in each component along with underlying causes.

#	Reference	GI Type**	Reference is used for extracting:		
			Components	Service Functions	Failures
1	Andenæs et al. (2018)	GR		Aesthetics, Runoff quantity control, Urban microclimate modification, Recreation	✓
2	Andenæs et al. (2021)	GR	✓		✓
3	Bąk and Barjenbruch (2022)	RG	✓	Urban microclimate modification	
4	Blecken et al. (2015)	BS, RG			✓
5	Bouchard et al. (2013)	BS	✓	Urban microclimate modification	
6	Braskerud and Paus (2022)	GR	✓	Runoff quantity control	
7	Cascone (2019)	GR		Runoff quantity control, Urban microclimate modification, Noise attenuation	✓
8	Cunningham (2017)	BS, RG, GR	✓	Biodiversity, Human health, Recreation	✓
9	Dagenais et al. (2018)	RG	✓		✓
10	Delgrosso et al. (2019)	BS, RG			✓
11	Ekka et al. (2021)	BS			✓
12	Filazzola et al. (2019)	BS, RG, GR	✓	Biodiversity	✓
13	Garmendia et al. (2016)	BS, RG, GR		Biodiversity	✓
14	Gunawardena et al. (2017)	BS, RG, GR		Urban microclimate modification	✓
15	Homet et al. (2022)	RG, GR	✓		✓
16	Kasprzyk et al. (2022)	RG	✓	Biodiversity	✓
17	Kavehei et al. (2018)	BS, RG, GR		Urban microclimate modification	
18	Kukadia et al. (2019)	RG	✓		✓
19	Li and Babcock (2014)	GR			✓
20	Melbourne Water (2013)	BS, RG	✓		✓
21	Mendez et al. (2011)	GR			✓
22	Minnesota Pollution Control Agency (2023)	BS, RG, GR	✓		✓
23	Müller et al. (2020)	BS, RG, GR	✓		✓
24	Nazarpour et al. (2023)	RG	✓	Runoff quality Improvement, Runoff quantity control	✓
25	Probst et al. (2022)	BS, RG, GR	✓	Urban microclimate modification, Recreation	✓

(continued on next page)

Table 1 (*continued*)

#	Reference	GI Type**	Reference is used for extracting: Components	Service Functions	Failures
26	Rasul and Arutla (2020)	GR		Urban microclimate modification, Recreation	
27	Robinson et al. (2019)	RG			
28	Rowe (2011)	GR	✓	Urban microclimate modification, Recreation, Roof protection, Noise attenuation	✓
29	Sañudo-Fontaneda et al. (2020)	BS		Runoff quality improvement, Human health	✓
30	Scolaro and Ghisi (2022)	GR	✓		
31	Shafique et al. (2018a)	BS		Runoff quantity control	
32	Shafique et al. (2018b)	GR		Human health, Recreation	✓
33	Shannon et al. (2020)	BS, RG	✓		✓
34	Silva et al. (2015)	GR	✓		✓
35	Stagge et al. (2012)	BS		Runoff quality improvement	✓
36	Tetra Tech (2016)	BS, RG			✓
37	Thurston (2017)	GR	✓		✓
38	Tolderlund (2010)	GR	✓		✓
39	Tomson et al. (2021)	GR	✓	Urban microclimate modification, Recreation	✓
40	Toronto and Region Conservation Authority (TRCA) (2016)	BS, RG, GR	✓		✓
41	USEPA (2021)	BS, RG, GR			✓
42	Vijayaraghavan (2016)	GR	✓	Runoff quality Improvement, Runoff quantity control, Urban microclimate modification, Recreation, Noise reduction	✓
43	Vollaers et al. (2021)	BS, RG			✓
44	Water Environment Federation (2022)	BS, RG, GR	✓		✓

* J: Journal articles; G: Guidelines; R: Reports; T: Thesis.
** BS: Bioswale, RG: Rain Garden, and GR: Green Roof.

classified the IEs into four main groups:

a) Service Function Failures:

This category focuses on failures that compromise one of the groups of service functions (e.g. runoff quantity control or pollutant removal) that GI systems are designed to perform.

a) Component Group Failures:

GI components that physically shape a part of the GI are grouped together. Component group failures are defined as separate IEs in the fault tree. This was done to indicate the location of the failures in the GI. These IEs pertain to the collective failure of components that serve a common principal role within the GI system. For instance, inlets collectively serve the purpose of channeling stormwater into the bioswale or rain garden.

a) Component Failures:

These events specifically target individual components comprising the GI system, isolating failures of critical elements such as pipes, check dams, or filter media layers. A component failure event is characterized by the malfunction, degradation, or failure of a single component, and it can contribute to broader system-level failures. Component failures are defined as separate IEs in the fault tree.

a) Failure Processes:

This category focuses on the underlying physical, chemical or other processes that can lead to the malfunction or failure of a GI system. Failure processes often involve intricate interactions between natural and anthropogenic factors. These may include changes in soil infiltration rates, sediment buildup, or chemical alterations in the GI environment. Fig. 2(i) shows the basic parts of a fault tree, along with the classifications used in this study.

2.5. Analysis of minimal cut sets

A fundamental challenge regarding GIs is the lack of comprehensive failure data (Cherqui et al., 2019a; Smith et al., 2023). Failure data for GIs have not been systematically collected or recorded with precision, and available data often lack detail and continuity, rendering quantitative failure analysis based on the fault trees an unfeasible task currently. However, the fault trees can still be utilized for a qualitative analysis, through the identification of the cut sets, which are combinations of events (BEs and IEs) that can cause failure (TE) to occur (Ren et al., 2017). To better demonstrate this concept, imagine a system with 2 components (e.g. two pumps), referred to as Component 1 and 2 (Fig. 2 (ii)). The system is designed in such a way that it fails if either component fails (e.g. power outage). In this system, failure of components 1 and 2 are two seperate examples of cut sets, defined as C1 = [A] and C2 = [B]. In qualitative FTA, the cuts sets with the lowest combination of events are known as Minimal Cut Sets (MCS). Each MCS contains a set of basic inputs necessary and sufficient to cause the top event. In other words, MCS has no redundant events, and if any basic event is removed from the set, the remaining events no longer lead to the top event (no longer a cut set). For example, in Fig. 2(iii) a hypothetical GI consists of one inlet, and an overflow outlet supported by an emergency outlet. If both of these outlets fail (e.g. due to clogging), then it can potentially lead to flooding. For the individual inlet, the single event of clogging could lead to failure of the GI. In this case, we have two cut sets, C1 = [A] and C2 = [B, C]. Both C1 and C2 are MCS, since they contain no redundant events, however, they have different orders. The order denotes the number of events that contribute to the TE. First-order MCS comprises a single event, implying that a single failure can trigger the system failure which may indicate a higher system vulnerability in comparison to a second-order MCS. In the above example, C1 is a first-order and C2 is a second-order MCS.

The MCSs provide useful insights into the critical components and service function failures of the system, which can aid in the development of effective risk mitigation strategies (Yazdi et al., 2023). Moreover, MCS offer a clear and concise representation of the chain of events required for a failure to occur, making it easier to pinpoint potential weaknesses in the system and develop targeted strategies to mitigate risks. For instance, if a fault tree contains cut sets with a few reoccurring events, controlling the occurrence of these basic events is a good

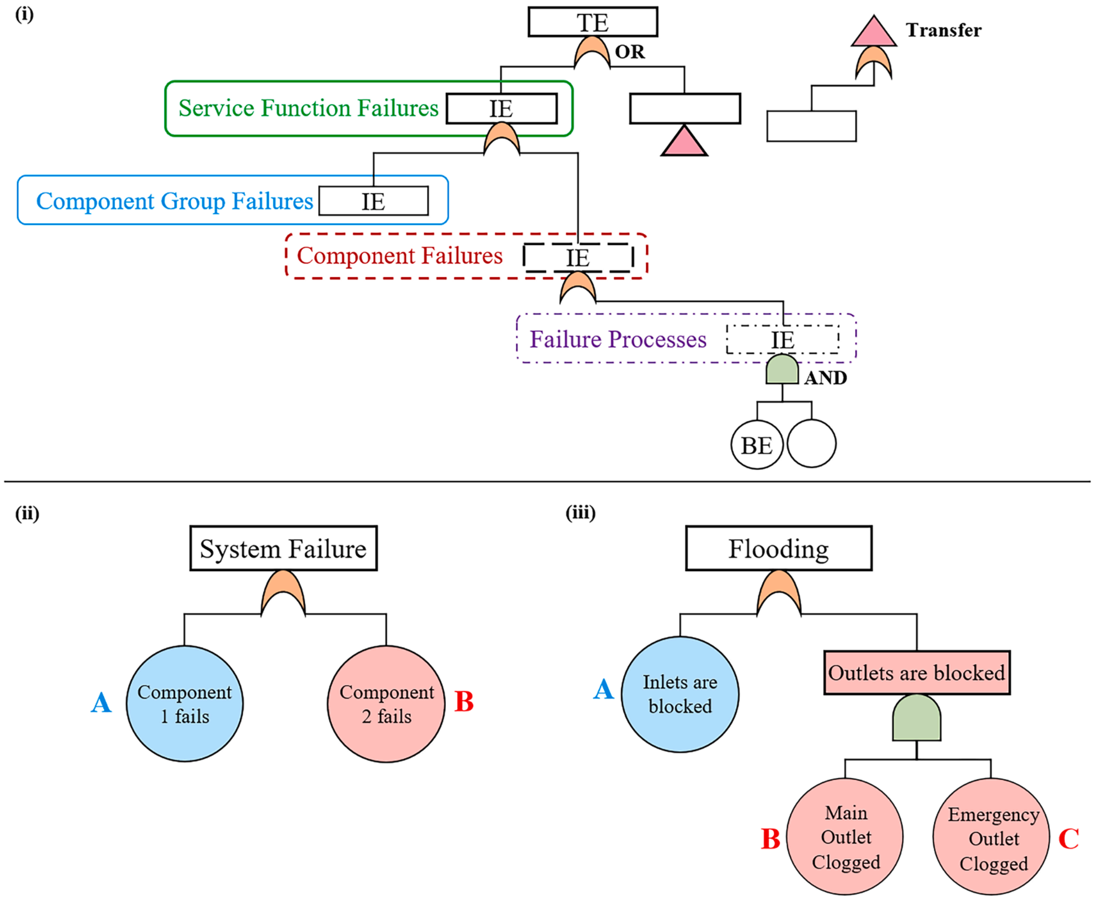

Fig. 2. (i) Components of a basic fault tree showing the Top (TE), Intermediate, (IE), Basic Events (BE), AND/OR Gates, and Transfer Gates. The figure illustrates how the 4 group of IE are differentiated using weighted and dashed lines. (ii) An illustration of the concept of cut sets in a fault tree, and (iii) An illustration of the concept of Minimal Cut Sets in a fault tree.

approach toward improving overall system reliability (Ruijters and Stoelinga, 2015). The identification of the MCSs, and subsequently recognizing the key events leading to failure, can also assist in devising effective strategies for collecting failure data. For instance, this may involve a focus on monitoring and data collection for the recurring events within the MCSs.

Due to the lack of systematic failure data collection, the current study will concentrate solely on the order and number of occurrences of failure events. Therefore, while the lack of specific failure data poses a limitation, the emphasis on the MCS offers a pragmatic means to guide future data collection strategies pertaining to the failure frequencies.

3. Results and discussion

3.1. Definition of study boundaries

From an asset management perspective, it is essential to link asset behavior and failures to the service function delivered. Understanding the link between asset performance and its quality of service provides insights toward enhancing overall operational efficiency (Le Gauffre and Cherqui, 2009; Parsons, 2010). That is why in this study, the term 'failure' pertains to the inability of the GI to provide each of the service functions it was designed for. Moreover, the methodology is applied on an asset-specific level, as our primary focus centers on examining representative types of GI, namely Bioswales, Rain Gardens, and Green Roofs (which are further described in Section 3.2). The selection of Bioswales, Rain Gardens, and Green Roofs for comprehensive failure analysis was done with the aim of achieving three key objectives:

1. To include a wide spectrum of mechanisms employed for runoff management within GIs, ranging from retention to infiltration strategies. Bioswales are designed to convey, treat, and infiltrate stormwater runoff received from roads and parking lots; rain gardens are designed to collect rainwater from a roof, driveway, or street; and green roofs are designed to capture and retain stormwater, reduce heat island effects, and provide insulation.
2. To incorporate a range of ownership structures, including individual/private systems and those that are accessible to the public. For instance, bioswales along a road may be owned by the road authorities, while rain gardens in the city could belong to the municipality or privately managed. Similarly, the ownership of green roofs can vary, with some being overseen by public agencies or private building owners.
3. To cover a wide array of installation sites, such as road/traffic facilities as well as building-adjacent placements. Bioswales are often used along streets, parking lots, and other paved surfaces, while rain gardens are typically located in residential yards and parks, and green roofs are installed on top of buildings.

In addition, the selected typologies of GI are also among the most extensively examined, as evidenced by studies such as Ferrans et al. (2022) and Khodadad et al. (2023), which facilitates the study since abundant resources on their maintenance and potential failure exists.

3.2. Identification of common GI components and groups

To better understand service functions of GI systems including bioswales, rain gardens, and green roofs, a review of existing literature and design guidelines was conducted to identify their commonly used components and their respective roles related to the service functions studied (see Table 1). Fig. 3 illustrates the components of the three GI measures.

Bioswales, also known as vegetated swales, or bioretention swales, are stormwater management measures designed with primary service functions of conveyance and pollutant treatment of urban stormwater runoff. Other processes integrated into bioswales include storage, plant uptake, and microbial degradation. Bioswales contribute to reducing heat island effects, provide aesthetics, and enhance urban biodiversity (Nazarpour et al., 2023).

Rain gardens, also known as bioretention cells, share a lot of similarities with bioswales in service functions they provide. Some variation known as stormwater planters are designed as "no infiltration" areas using an impermeable liner or container (Toronto and Region Conservation Authority (TRCA), 2016; Kasprzyk et al., 2022). Rain gardens should be planted with vegetation that is tolerant to local climate conditions without the need for fertilizers. The depression or ponding area can be classified into three sections, where lower areas need vegetation that can survive in wetland conditions, but also tolerate periodic droughts. In the mid zones often species such as grasses or low shrubs are used. The vegetation in the mid zone serves two important purposes: it shields the side slopes, preventing erosion, and helps maintain the storage capacity. In the high zones, plants with dense root structure and/or vegetative cover are favored for their ability to act as pollution filters and tendency to slow water velocity (Toronto and Region Conservation Authority (TRCA), 2016).

Green roofs, also known as vegetated-, eco-, or living roofs, contribute to aesthetics, environmental, and economic advantages including stormwater management, heat island reduction, and improved energy efficiency of buildings (Shafique et al., 2018b). Green roofs typically consist of several key components, such as vegetation, substrate, protective layers, drainage, and insulation (Vijayaraghavan and Raja, 2014). There are two main types of green roof, namely intensive and extensive. Intensive green roofs are characterized by their deeper substrate layers, which allow for the cultivation of a wide range of plant species, including trees and shrubs (Cascone, 2019). These roofs are akin to traditional gardens, but they offer enhanced stormwater retention and filtration, biodiversity and opportunities for recreational spaces and urban farming. On the other hand, extensive green roofs have shallower substrate layers, making them well-suited for the growth of low-maintenance, drought-tolerant vegetation such as grasses, sedums, and other hardy plant species. These roofs are lighter in weight, making them more suitable for retrofitting existing buildings and covering large roof areas (Cascone, 2019).

Table 2 lists the most common components for bioswales, rain gardens and green roofs, extracted from the references provided in Table 1, along with their respective roles. Components are classified based on their role into 8 different component groups.

3.3. GI service function failures and their potential causes

Based on the principal roles identified in Table 2 and the failure extraction process described in Sections 2.2 and 2.3, the GI failures were classified under 3 main failures corresponding to provided service functions:

a) Runoff quantity control failure

Runoff quantity control failure in the context of GI refers to situations where the designed systems or elements intended to manage stormwater runoff prove inadequate in effectively mitigating flooding or attenuating the volume of runoff (as designed for), leading to increased risk of urban flooding, and potential damage to surrounding areas. Such failures can be attributed to various events, including poorly designed components, clogging of inlets or outlets, reduction of retention volume, misuse (e.g. by inhabitants) or improper maintenance.

a) Runoff quality control failure

Runoff quality control failures pertain to instances where the GI or its components fail to effectively remove pollutants from stormwater runoff or inadvertently become sources of pollution themselves. One of the primary objectives of GIs is to mitigate the impact of urban runoff on water quality by capturing, filtering, and treating pollutants before they enter natural water bodies. Quality control failures may arise due to

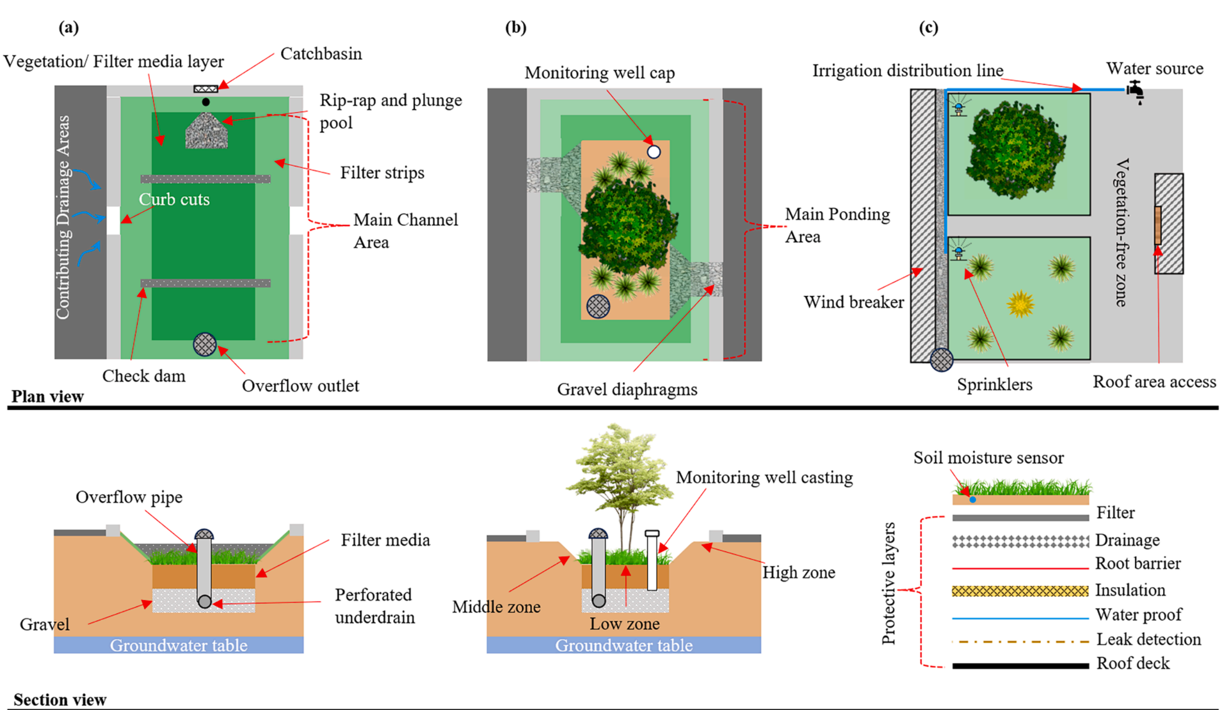

Fig. 3. General plan and section views of (a): Bioswales, (b): Rain Gardens, and (c): Green Roofs.

Table 2
Common GI components for bioswales, rain gardens and green roofs along their respective functions (Blue cells identify component only for bioswales/ rain gardens; Green cells identify component only for green roofs; White cells identify components for all three types of GI).

Component group	Component	Principal role(s)
Contributing drainage area	Roads, parking lots, rooftops, and filter strips.	Direct runoff to GI
	Downspout disconnection	Redirect water to GI
	Forebay	Reduce the flow velocity, prevent erosion, sedimentation, pollutant removal, promote infiltration, diffuse the flow
	Pretreatment devices/ features (e.g. catchbasin inserts, eavestrough screens, oil and grit separator, and gravel diaphragm)	Capture sediment or pollution before it reaches the filter bed, remove trash and debris, minimize clogging of the inlet, diffuse the flow
Inlet	Curb cuts, flush curbs, spillways, pipes, pavement edges, catchbasin inserts, and trench drains.	Direct water to the GI
	Rip-rap and plunge pool	Prevent erosion
	Splash blocks, plunge area	Prevent the downspout flow from eroding the soil
Main channel or ponding area	Stone or concrete check dams	Reduce the flow velocity, prevent channel surface erosion, sedimentation, pollutant removal, promote infiltration
	Vegetation	Landscaping, reduce the flow velocity, prevent channel surface erosion, pollutant removal, reduce heat island effect through evapotranspiration, air quality improvement, enhancing biodiversity, promote recreational activity, increase property values
	Erosion control measure (e.g. Matting)	Prevent surface erosion from rain or wind scour while vegetation is becoming established
	Filter media layer	Promote infiltration, carbon sequestration, improve energy efficiency of the building (insulation), noise attenuation, support urban agriculture
	Mulch layer	Keep the soil moisture for plant survival, suppresses weed growth, maintain organic matter, promote denitrification
	Choker layer	Prevent migration of finer filter media into the underlying storage reservoir aggregate
	Main channel, Surface grade	Conveyance of storm water, ensure a maximum ponding time of 48 hours, sedimentation, promote infiltration, snow storage and treatment
	Side slopes	Create a ponding area, create primary zones in ponding area (Low, Mid, and High zone)
	Low zone ponding area	Temporary water storage, ensure a maximum ponding time of 48 hours, water treatment, sedimentation, promote infiltration, snow storage and treatment, holds water during rainfall events and drains after the event (highly saturated area), infiltration and absorption of water
	Mid zone ponding area	Water storage during 2 – 100-year rainfall events, filtration, and evapotranspiration
	High zone ponding area	Transition area from bioretention to swales or other practices, filtration, reduce the flow velocity
Protective layers	Insulation layer	Maintain indoor temperatures, reduces heat transfer
	Water-proofing membrane	Protect the roof deck and insulation layer from water damage
	Root barrier	Protects the water-proofing membrane from root penetration and degradation by microbial activity
	Filter fabric or Geotextile	Retain growing media and prevent their migration into the drainage layer
	Leak detection system	Check for the presence of leaks (periodically) in the water-proofing membrane

(continued on next page)

Table 2 (*continued*)

Outlet	Overflow, ditch inlet, culvert, and overflow swales in inline drainage systems.	Drainage, convey flow to another drainage system/ water bodies
	Flow splitters or bypass channels used in offline drainage systems	Allow only the design runoff volume to enter
	Downspout	Convey flows exceeding the storage capacity of roof to the drainage network or GIs on street level
	Perforated underdrain pipe	Ensure a maximum ponding time of 48 hours
	Drainage layer	Collect excess water that is not absorbed by the vegetation, growing medium, or geotextile. It directs the excess water to outlet structures, and conveyed via the roof drainage system to another stormwater GI or the municipal storm sewer system
Monitoring	Monitoring wells	Verify and track drainage time
	Soil moisture sensors	Optimize irrigation process, automate irrigation in dry periods, suppress irrigation after rain events
Building area and protection	Vegetation free zone	Separates the green roof perimeter from the roof perimeter and other structures on the roof (e.g., vents), which is kept devoid of vegetation and natural debris; should be maintained as a fire prevention measure, create access path for maintenance, and reduce wind uplift
	Wind breakers (e.g. parapets)	Prevent wind scour of growing medium, protect from wind uplift of green roof layers
	Fences	Prevent the GI area from foot traffic, break in, and vandalism.
Irrigation system	Sprinklers, pipeline, and power cables.	Provide regular irrigation to keep vegetation in dry periods, maximize evapotranspiration.

factors like insufficient maintenance, improper design, or the presence/ accumulation of toxic materials within the GI infrastructure.

a) Additional service function failures

Besides their impact on water related risks, GIs provide a wide diversity of ecosystem services essential to human life, understood as the co-benefits obtained from GI implementation. The term 'additional' is used to address these co-benefits, as they are often not the key reason behind adapting GIs in practice . Some examples of additional service functions provided by GIs are landscaping, biodiversity enhancement, improving air quality and provision of recreational services. Green roofs also provide the additional co-benefit of protecting rooftops. Failure in providing these services can be attributed to different components in GIs such as vegetation, soil, insulation layers, protective layers, and/or structural issues.

As stated in studies such as Hoover et al. (2023), while multi-functionality remains a dominant rationale behind GI adaptation, in reality more weight is given to stormwater management capabilities when it comes to design and implementation of GIs, and available literature are more focused on maintaining water quality and quantity control functions. Furthermore, as failure data are not properly recorded, it is not possible to describe the failure process of service functions on higher scale (e.g. GI impact on urban temperatures). That is why in this study failures are classified into the abovementioned groups. However, data collection efforts and further research is needed on developing guidelines and control actions specifically aimed at maintaining additional service functions of GIs (Langeveld et al., 2022).

3.4. *Constructing the fault trees*

A total of three different fault trees for three groups of GI service function failures were constructed. The resulting fault trees are visualized in Figs. 4, 5 and 6. An interactive version of the fault trees is also available at https://mbahrami9264.github.io/FaultTreeAnalysisGI. The trees consist of 45 IEs and 54 BEs, with comprehensive descriptions provided in the interactive version of fault trees as well as berifly listed in Tables 3 and 4. A comprehensive structure for the GIs was created based on the events that could possibly lead to each service function failure, grouping similarities of the three types of GIs together and specifying the differences wherever necessary.

In Table 4, certain events recognized as 'Anthropogenic influencers' are highlighted. These are events that are influenced or caused solely by human activities such as human induced changes in the area, suggesting that the failure is triggered by activities unrelated to the inherent design or function of the GI. These events were recognized based on the literature review process as described in Section 2.3. Moreover, in Table 4 each event is identified with its 'Stage', which denotes the life cycle stage in which the BE most probably occur. For example, 'clogging due to sediment accumulation' often happens right after realization due to construction errors, or after the GI has been in operation for a while, so the event usually appears in the Construction and operation phase (denoted by C/ O in Table 4). In comparison, a problem such as 'Constraints to use rooftop area' most probably is rooted in design or construction phase failures. It is important to note that some of the extracted events such as IE11, 12 and 14 are highly dependent on other factors such as frequency and intensity of rainfall events. In such cases, the failure event is considered for the intended performance of GI in regards to design criterias such as design rainfalls.

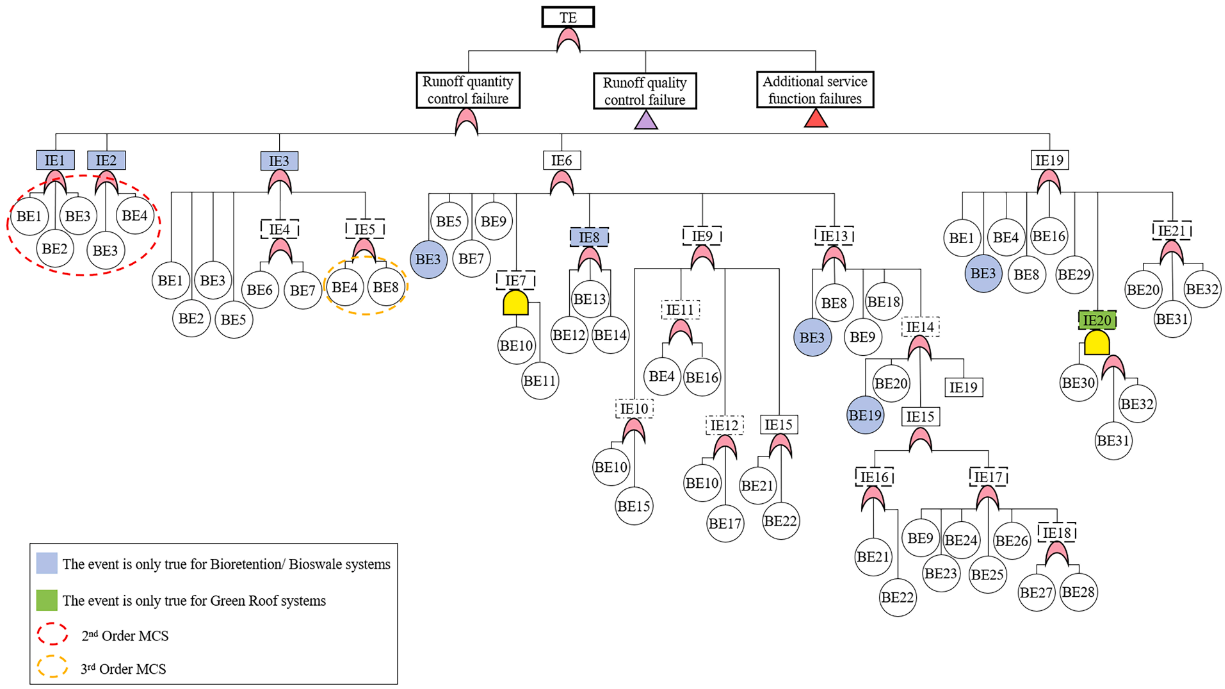

Fig. 4. Basic fault tree for Runoff Quantity Control Failure of selected GIs. An interactive version with detailed description of events is available at https://mbahrami9264.github.io/FaultTreeAnalysisGI.

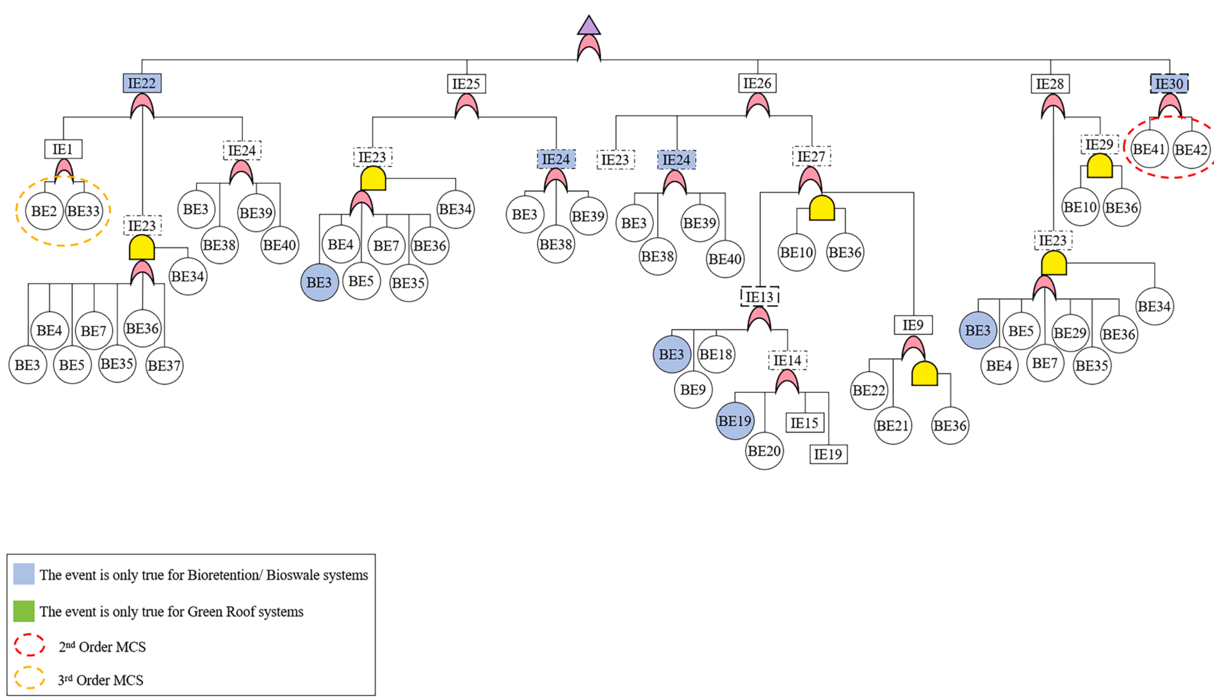

Fig. 5. Basic fault tree for Runoff Quality Control Failure of selected GIs.

To demonstrate how the information in the fault trees is structured, blockage of outlets (IE21) from the runoff quantity control failure tree (Fig. 4) is explored as an example. IE21 have three different branches, each showing an individual basic event (BE20, BE31, and BE32). These events are connected using an OR logical gate which indicates any of these three events on their own can cause the occurrence of IE21. For example BE20 is freezing of the under drain pipe, which can decrease or block the outflow from the under drain. When IE21 occurs, it causes an instance of blocked outlets (IE19), hindering the operation of a rain garden or a bioswale. In Fig. 5 scouring around outlet pipes or channels (IE29) is branched into two events using an AND gate, indicating these events need to happen together to cause IE29. The first event is wash off (BE36) which can happen when there is no vegetation to hold down the soil layer (BE10, plants not thriving). The occurrence of both of these events together can affect the TSS concentration of outflow, hence decreasing its quality. This is why this event has been categorized as part of the runoff quality control failures.

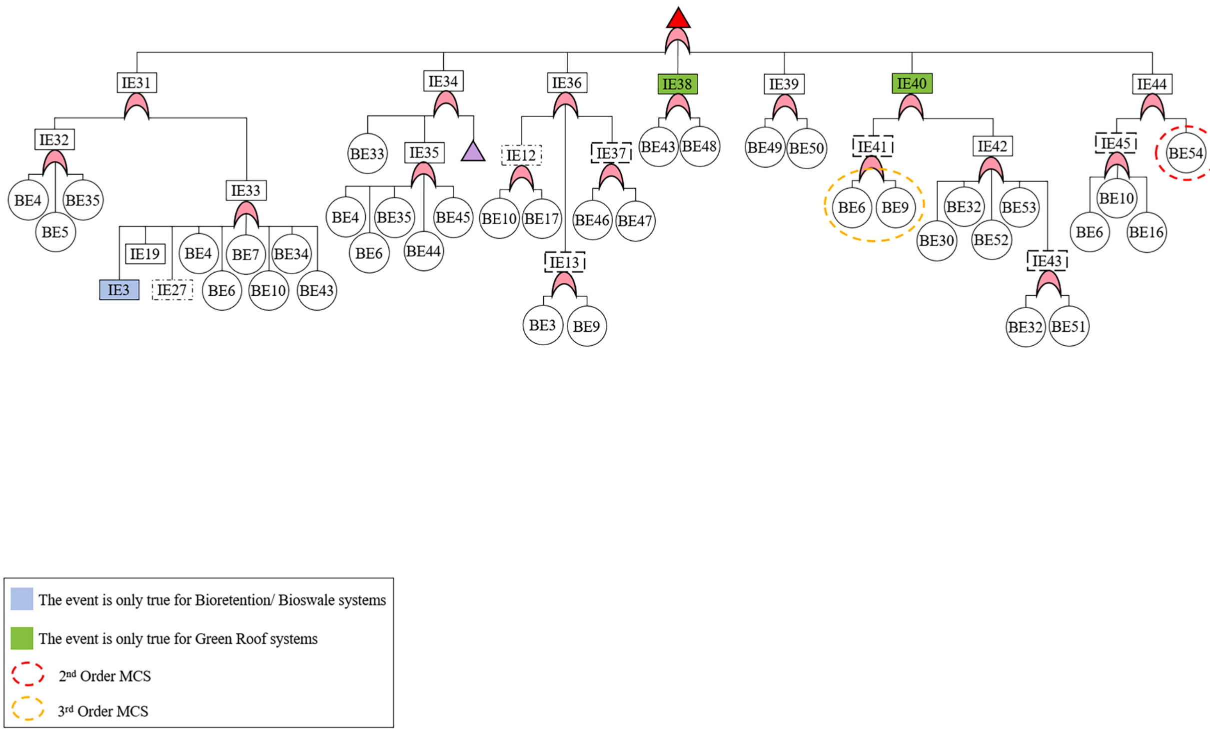

Fig. 6. Basic fault trees for Additional Service Functions of selected GIs.

Table 3
List of intermediate events used in the fault trees.

Symbol	Name	Reference*	Symbol	Name	Reference*
IE1	Changes in the contributing drainage area	20, 44	IE24	Changes in management of the area	20, 44
IE2	No inflow from contributing drainage area	40, 43	IE25	Pollution at inlets	35
IE3	Blocked inlets	36, 41	IE26	Pollution at main channel or ponding area	9, 21
IE4	Blocked curb cuts	11, 43	IE27	Deterioration of components	24, 40
IE5	Blocked catch basin inserts	40	IE28	Pollution at outlets	4
IE6	Main channel or ponding area deteriorated	11, 29	IE29	Scouring around outlet pipes/ channels	10, 23
IE7	Damage to side slopes	11, 41	IE30	Pollution intrusion from monitoring well	40, 44
IE8	Check dam deteriorated	8, 11	IE31	Aesthetic failures	36, 37
IE9	Inadequate water retention by vegetation	37, 44	IE32	Unpleasant odors from ponding area	36
IE10	Low vegetation roughness	44	IE33	Unattractive appearance of ponding area	16, 18
IE11	Low flow rates	40, 41	IE34	Health hazards	14, 24
IE12	Low evapotranspiration	14, 25	IE35	Hotspot for diseases	23
IE13	Inadequate water retention by soil	10, 33	IE36	No effect on urban microclimates	37, 39
IE14	High soil moisture	19, 44	IE37	No shading effects	16, 25
IE15	Irrigation system malfunction	37, 38	IE38	Ineffective noise attenuation	32
IE16	Excessive irrigation	37	IE39	Limited recreational potential	32
IE17	Leakages/ bursts in the distribution line	34, 37	IE40	Damage to the structural integrity of the roof	34, 38
IE18	Pipe joint leakage/ break	22, 44	IE41	Degradation of non-vegetated area	34, 37
IE19	Blocked outlets	4, 36	IE42	Degradation of protective layers	34, 37
IE20	Blockage of drainage layer	44	IE43	Leak detection system malfunction	38
IE21	Blocked under drain pipe	34, 36	IE44	No effect on biodiversity enhancement	12, 13, 16
IE22	Pollution from contributing drainage area/ pretreatment devices	35	IE45	Insufficient plant species	13, 16
IE23	Resuspension of unwanted things	22, 35			

* This column specifies the cited resources in Table 1 from which the event is identified.

3.5. Analysis of minimal cut sets

MCSs represent the smallest set of event combinations leading to a TE, some examples of which are indicated in Figs. 4, 5 and 6 (specified by red and orange dashed circles). To investigate the applicability of the MCS analysis, 2nd and 3rd order MCSs from the resulting trees, denoting sequences of events with only 2 or 3 events that could lead to the occurrence of the TE, were first examined. Fig. 7 illustrates the results of the analysis of theseMCSs. To streamline the presentation, bioswales and rain gardens are grouped together due to their similarities (top row; a(i), b(i), and c(i)), while green roofs are presented separately (bottom row; a (ii), b(ii), and c(ii)). Additional service function failures are also color coded based on their groups.

The analysis reveals that in bioswales and rain gardens, MCSs primarily lead to runoff quantity control, aesthetics, and quality control failures (32 %, 28 %, and 24 % of all MCS, respectively), whereas in green roofs, they predominantly lead to aesthetic failures (31 %), followed by quantity (20 %), and quality (11 %) failures (Fig. 7a(i) and a (ii)). It should be mentioned that a certain level of subjectivity is involved regarding what constitutes as an aesthetic failure, and GI visibility can also be a deciding factor on its importance. The remainder of MCSs in bioswales and rain gardens contribute to failures in improving

Table 4
List of basic events used in the fault trees, their respective failure stages, and the references they were extracted from. Anthropogenic influencers indicating events caused only by human activities are highlighted.

Symbol	Name	Stage*	Reference**	Symbol	Name	Stage*	Reference**
BE1	Obstruction caused by external elements (e.g. new infrastructure or parking cars)	D/ C/ O	34, 43	BE28	High water pressure	D/ C/ O	22, 40
BE2	Deterioration of nearby infrastructures (e.g. roads or parking lots)	O	23	BE29	Mulch accumulation	O	44
BE3	Winter road maintenance causing deterioration (e.g. snow pileup or heavy equipment)	O	22, 40, 41	BE30	Layers exposed	C/ O	34
BE4	Trash accumulation (e.g. street litter or plastic bags)	O	20, 41	BE31	Migration of filter media into the drainage layer	O	34
BE5	Green waste accumulation (e.g. grass clippings or leaves)	O	15, 40	BE32	Root penetration	O	40, 44
BE6	Invasive plants taking over	O	34, 36	BE33	Change in land use patterns in the area	D/ O	23
BE7	Sediment buildup on the surface	O	11, 41	BE34	Ineffective or neglected clean up	O	22, 36
BE8	Clogging (due to sediment accumulation, compation, or dry periods)	C/ O	34, 40	BE35	Animal excrement	O	40
BE9	Deterioration caused by external factors (e.g. foot traffic or heavy equipment)	D/ O	2, 22	BE36	Wash off (e.g. sediments, soil particles)	O	36, 40
BE10	Plants not thriving	D/ O	20, 41	BE37	Pollution from oil & grit separator	O	22, 40
BE11	Soil erosion	O	11, 36	BE38	Increase in traffic in the area (e.g. source of oil leaks, heavy metals, or hydrocarbons)	O	23, 27
BE12	High check dam invert	D/ C/ O	41	BE39	Increase in construction in the area (e.g. source of construction debris/waste, paints compounds or detergents)	O	23, 40, 44
BE13	Appearance of cracks in concrete	C/ O	44	BE40	Excessive use of fertilizers, pesticides, and herbicides	O	40, 41
BE14	Check dam stones moved upstream	O	40, 41	BE41	Monitoring well's cap broken	O	11, 40
BE15	Too short vegetation	D/ C/ O	4	BE42	Well casing leakage	C/ O	40
BE16	Overly dense vegetation	D/ C/ O	20, 44	BE43	Inadequate vegetative cover	D/ C/ O	9, 12
BE17	Sunlight obstruction (by obstacles or trees)	D/ C/ O	34	BE44	Pathogen and bacteria contamination	O	24
BE18	Freezing of soil top layer	D/ C/ O	22, 33	BE45	Appearance of mosquitos or other insects	O	22, 41
BE19	High groundwater level	D/ C/ O	24, 41	BE46	Loss of shading due to damages	O	14, 25, 40
BE20	Freezing of under drain	O	1, 27	BE47	Trees not thriving	D/ C/ O	20, 40, 41
BE21	Sensor malfunction	C/ O	25	BE48	Insufficient soil depth	D/ O	28, 42
BE22	Uneven irrigation	D/ C/ O	22, 38	BE49	Constraints to use rooftop area	D/ C	34, 37
BE23	Pipe corrosion	O	22	BE50	Vegetation free zones not available	D/ C	40
BE24	Drips/ sprinklers leaking	O	40	BE51	Physical damage to power cables	C/ O	44
BE25	Freezing of components	O	20, 40	BE52	Detachment of layers from roof	C/ O	34
BE26	Clogging of drips/ sprinklers	O	40	BE53	Wind uplift	D/ C/ O	34
BE27	Poor joint sealing	C/ O	22, 44	BE54	Degradation of GI habitat	D/ C/ O	12, 13

* Specifying the stage in GI life when the BE may occur, D: Design, C: Construction, O: Operation.
** Specifying the resources in Table 1 from which the event is identified.

urban microclimate (6 %), human health (6 %), and biodiversity (4 %), whereas for green roofs the remaining portion of MCSs is primarily associated with failures in improving urban microclimate (9 %), roof protection (9 %), human health (8 %), biodiversity (6 %), noise attenuation (3 %), and recreation (3 %). However, it is worth mentioning that some of the additional service functions such as improving biodiversity are often attributed to cumulative effects of GIs on a network level (Whitford et al., 2001; Xing et al., 2017), and with the promotion of GI multifunctionality it is imperative to study how failures affect these service functions in different scales and identify significance thresholds. For instance, the contributions of small GIs to biodiversity may be modest but should not be disregarded (Riva and Fahrig, 2023).

Additionally, the high percentages of MCS in quantity and quality failures in bioswales and rain gardens can be attributed to winter maintenance practices, the interactions between bioswales and rain gardens with nearby infrastructure, urban development, and human activities. This is evident from BEs with the highest contribution to MCS such as BE3 (deteriorations from winter maintenance), BE4 (trash accumulation), and BE1 (obstruction by external factors). These BEs along with BE16 (dense vegetation) also contribute highly to aesthetic failures (Fig. 7b(i)). In green roofs, BEs contributing to higher rates of aesthetic, quantity and quality control failures are trash accumulation (BE4), clogging due to sediment accumulation (BE8), deterioration by external influences (BE9), and vegetation problems (BE6 and BE16) (Fig. 7b(ii)). The recurrent BEs for all the three GIs, namely BE4, 8, and 16, reveal a noteworthy pattern where, despite the diversity of GI types and failures, certain BEs may emerge as common root causes for distinct service function failures. BE4, 8 and 16 affect service functions such as aesthetics, quantity, quality, biodiversity, and human health in all three types of studied GIs. Although there is a need for data to further prove the above reasoning and discussion, this finding shows that strategic targeting of certain BEs may enhance operation and maintenance of GIs among a broad range of service functions.

For all three types of GI, the MCSs primarily stem from the ponding areas, followed by the outlets. About 50 % of all MCS in bioswales and rain gardens, and more than 60 % in green roofs were related to BEs rooted in the ponding areas (Fig. 7c(i) and c(ii)). It should be emphasized that, based on the color coding presented in this figure, failures in

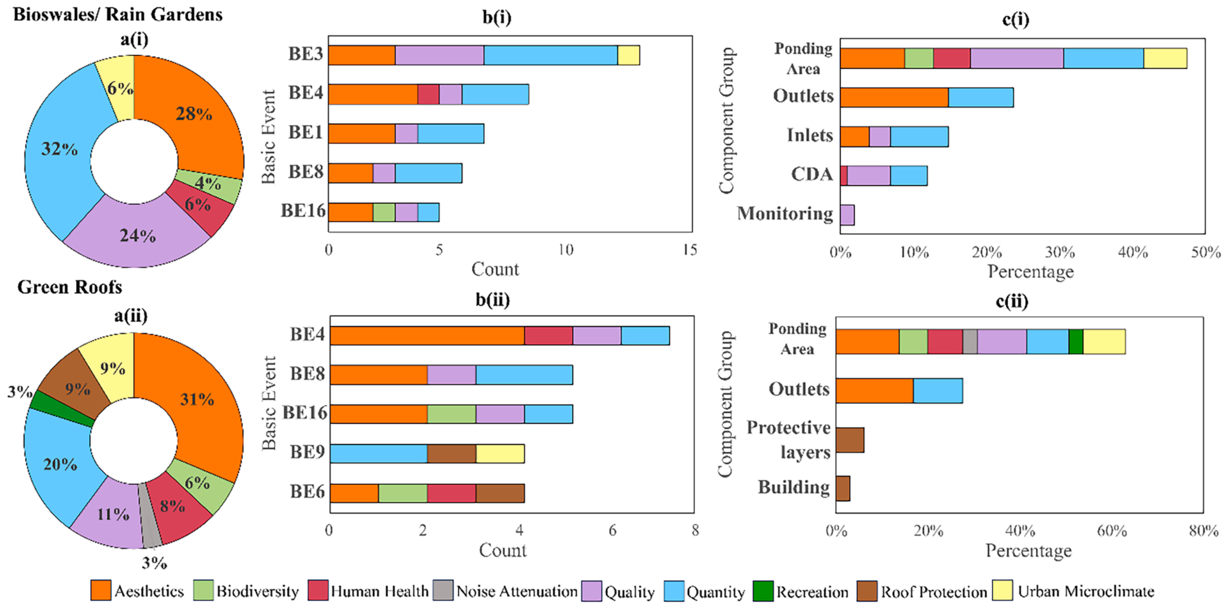

Fig. 7. MCS analysis of 2nd and 3rd order BEs; (a(i), a(ii)) Percentage of MCS based on service functions, (b(i), b(ii)) Top-5 BEs with the highest contribution in different MCS, and (c(i), c(ii)) Component groups with the highest contribution in different MCS.

ponding areas can have negative effects on nearly all the service functions of the studied GI types. In comparison, approximately 25 % of MCS in bioswales, rain gardens, and green roofs can be traced back to the outlets. The components in this group are susceptible to quantity control and aesthetic failures.

In general, the results from the MCS analysis underscore a pattern where the majority of often occurring BEs are related to anthropogenic factors such as winter maintenance practices, trash and debris accumulation, and obstruction or deterioration caused by external influencers affecting GI operationality. Anthropogenic factors among the MCS are affecting GIs performance by hindering inflow to the GI (IE1, 2, 3), causing component failures (IE6, 13, 19), increasing the inflow of pollutants into the GI (IE22, 24) and affecting other service functions (IE31,35, and 36). These finding align with those of other studies such as Vollaers et al. (2021) and Homet et al. (2022), which highlight interfaces between GIs and other urban infrastructure or areas are prominent sources of failure. Moreover, the MCS are intrinsically linked to the ponding areas, meaning that although the most frequently occurring BEs such as BE 3, 4, and 8 are related to external factors, they are contributing to component failures inside the GI ponding areas. Consequently, the impact of anthropogenic factors should be considered when devising strategies for collection of failure data from GIs. Strategies such as collection and integration of social and geospatial data including urban development patterns, construction, and land use changes in the contributing drainage area could provide insights into their deterioration processes. An example of this is the method used by Homet et al. (2022) to map urban areas where GIs are susceptible to litter, and sediment build up. Combined with inspections to record instances of occurrences, insights regarding frequencies and scale of impact of such factors could be extracted.

In addition to information provided by the MCS analysis, studying all conceivable combinations of cut sets suggests some BEs could potentially impact GI performance in relation to a wide range of service functions. Table 5 highlights BEs with the potential to serve as a primary contributor to the highest number of distinct service function failures. Accordingly, BE6 (invasive plant takeover), BE9 (deterioration due to external influences), and BE10 (plants not thriving) can collectively influence over half of the discussed service functions within GIs. BE6 and 10 are directly related to failures by vegetation, while BE9 could be attributed indirectly to filter media failures, since it is a root cause to IE6, 13, 17, and 36.

Furthermore, data collection efforts should focus on the role of components in ponding areas and the need for monitoring to comprehensively capture relevant variables and dynamics. The interactions that exist among component failures need to be considered for prioritization. In order to study such interactions, all the cut sets for the fault trees were analyzed to identify failure events that were rooted in cascading failure effects. This was done by studying the cut sets step by step, going from the basic event and following the sequence of events to reach a component failure. Each instance was recorded as [BE -> Component Failure]. For instance, plants not thriving could potentially lead to damages in side slopes, so it was recorded as vegetation -> side slopes

Table 5
BEs that have the potential to act as a root cause to the highest number of distinct service function failures.

Symbol	Event Name	Aesthetics	Bio-diversity	Human Health	Roof protection	Urban microclimate	Runoff quantity control	Runoff quality control
BE9	Deterioration by external influences	✓			✓	✓	✓	✓
BE6	Invasive plants taking over	✓	✓	✓	✓		✓	
BE10	Plants not thriving	✓	✓			✓	✓	✓
BE3	Winter road maintenance causing deterioration	✓				✓	✓	✓
BE4	Trash accumulation	✓		✓			✓	✓
BE16	Overly dense vegetation	✓	✓				✓	✓
BE32	Root penetration	✓			✓		✓	✓
BE30	Layers exposed	✓			✓		✓	✓

[BE10 -> IE7].

To better explain this effect, Fig. 8 illustrates the relationship between component failures in bioswales, rain gardens and green roofs, for each of the distinct service function failures. The figure was made based on the number of times each failure interaction was repeated. Anthropogenic factors contributing to failures were not considered in this graph, to emphasize only the component interactions. Based on this figure, vegetation-related failures emerge as the primary source of performance issues in all service function failures. BEs originating from vegetation can lead to problems in under drains (BE32), inlets (IE3, BE5, 6, 16), outlets (BE10, 16), filter media (BE11, 29, 36) or interfere with operation of protective layers in green roofs (BE32), among other potential consequences. In Fig. 8(ii) vegetation failure (BE10) can have a cascading effect which causes failures in filter media (BE36) that could lead to subsequent failures in drainage layers (BE31), inlets (BE36) or the outlets (BE29). Other important sources of influence are irrigation systems, filter media, and green roof's protective layers.

It is highly recommended that the divergence in sources of failure illustrated through Figs. 7 and 8 and Table 5 be addressed when making plans for failure data collection, to enable a comprehensive and more nuanced analysis of GI failures through FTA. Qualitative and quantitative data can be collected based on design objectives of GIs. Inspections should be tailored to the failure patterns identified, and other types of qualitative data such as maintenance logs, photos, issues reported by owners, and interviews with operators and experts could potentially be used for improving or validating the quality of data. If failure data of GIs are collected, there is a potential to transform the number of occurrences of each BE in a fixed period of time into probabilities using statistical analysis methods such as the Poisson distributions (ten Veldhuis et al., 2011) or fuzzy set theory (Abedzadeh et al., 2020). For quantitative data collection, low-cost sensors (Cherqui et al., 2019a) and scheduled performance tests can be used to monitor infiltration rates, soil moisture levels, plant conditions, pollutant removal rates, runoff volume reduction, and other failure processes involved. Such practices could facilitate early detection and mitigation of potential failures, reducing the chances of costly damage and disruptions faced by reactive maintenance practices. By systematically analyzing fault trees, maintenance teams can identify weaknesses in GI systems and take preemptive actions, leading to improved reliability and performance over time. In longer term, information gathered on the failure processes in GIs could be used for improving their design according to operational conditions and possible failure processes.

4. Conclusion

GIs have been widely adopted as a modern solution to a multitude of urban challenges. However, similar to other infrastructure, GIs are subject to deterioration which affects their long-term performance. A precondition for GIs proactive operation and maintenance is understanding their underlying failure processes and start recording data accordingly. In this respect, this study introduces a method for constructing fault trees for GIs and identifying events and components of interest for future attempts at failure data collection. Based on literature, commonly adopted components and their principal roles were extracted to construct fault trees for three different types of widely adopted GIs. In the next step, all the events that lead to failure in each of the examined GIs were identified and classified into 45 IEs and 54 BEs. Qualitative analysis was performed on the constructed fault trees, concluding in three main findings:

– In the absence of failure data to perform quantitative analysis, qualitative MCS analysis of fault trees is an informative method to pinpoint events that could potentially cause GI failure with the lowest combination of BEs. Analysing MCSs are important because if only one of the events in the MCS is controlled, the undesired outcome could be potentially stopped. Through the MCS analysis some events emerged as common root causes of distinct service function failures, such as trash accumulation, clogging due to sediment accumulation, and overly dense vegetation. These BEs affect quantity and quality control, aesthetics, human health, and biodiversity service functions in GIs and could be potential events of interest for monitoring, maintenance, inspection, and data collection activities.

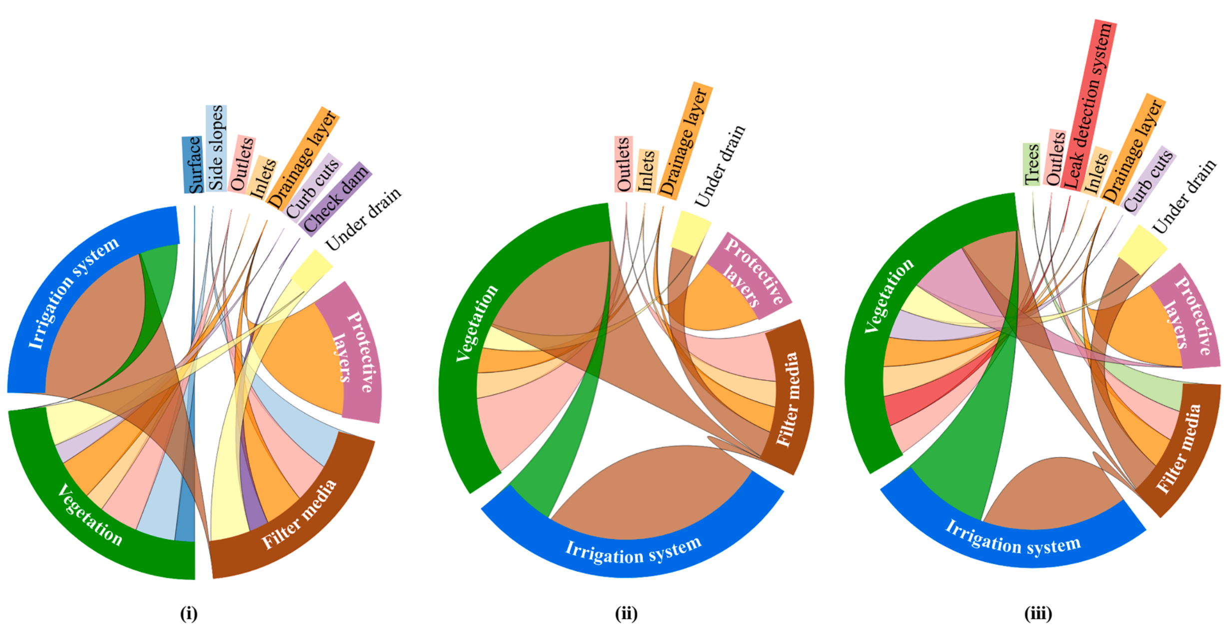

Fig. 8. Failure interactions between components of studied GIs; (i) Runoff quantity control, (ii) Runoff quality control, and (iii) Additional service function failures. Each component is depicted as a segment around the circle, with interactions between components shown as arcs connecting the segments. Components are distinguished by unique colors. The width of each arc indicates the number of times each failure interaction was repeated in the cut sets, while the color highlights the component affected by the interaction. When component failures can influence each other, the arc color is determined by the component with the narrower width.

- Although recurring MCSs include events pertaining to anthropogenic activities near the GIs, such as winter maintenance practices, construction, or urban development, it is noteworthy that these BEs lead to failure of components situated in the ponding areas of GIs. Components in this area, such as vegetation and filter media layer, also play a bigger part in the failure of other GI components through cascading failure effects. Consequently, considering the interconnectedness of GIs with their surrounding environment and component failure interactions could improve plans for asset management of GIs. This involves prioritizing inspections and repairs based on the components that have a wider impact on other components. The results can also be used for implementing redundancies during the design steps. For instance, based on the expected service functions the designer could consider using GIs with/ without vegetation (For example opting for a dry swale instead of vegetated one).
- Among all the possible cut sets extracted from fault trees, certain BEs (i.e. plants not thriving, invasive plants taking over, and deterioration caused by external influences) have the potential to disrupt more than half of distinct service functions provided by the studied GIs. Such events could significantly compromise those GIs performances, particularly when multifunctionality stands as a central criterion for GI adaptation.

In addition to these results, if systematic data collection methods are developed and exhaustive data are collected, the constructed fault trees in this study could potentially be used to compute the frequency of GI failures, and identify critical failure paths and components. This could create opportunities for research on modeling the deterioration processes in GIs, scheduling of their inspection and maintenance, and addressing the vulnerabilities of their design. As current study solely relied on available literature, future research endeavors are needed to incorporate insights from maintenance teams and stakeholders to create a more comprehensive understanding of GI failure mechanisms. Further research is needed to address inspection and data collection efforts, such as designing inspection sheets and data bases and planning data collection frequencies accordingly. The impact of addressing minimal cut sets or failure interactions in optimizing maintenance activities could further clarify the applicability of the suggested approach. There is also need for studies that explore the scalability and applicability of the proposed fault tree approach across different types of GI installations, varying in size, complexity, and geographic location. Moreover, to support multifunctionality in GI design, further research is needed to identify significant failure thresholds for various service function failures.

CRediT authorship contribution statement

Mahdi Bahrami: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Bardia Roghani:** Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing. **Franz Tscheikner-Gratl:** Conceptualization, Supervision, Writing – review & editing. **Marius Møller Rokstad:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgment

This research received financial support from Norwegian University of Science and Technology's LIFELINE 2050 project, a part of the Green 2050 center (https://www.ntnu.edu/green2050).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2024.121676.

References

Abedzadeh, S., Roozbahani, A., Heidari, A., 2020. Risk assessment of water resources development plans using fuzzy fault tree analysis. Water Resour. Manag. 34 (8), 2549–2569. https://doi.org/10.1007/s11269-020-02578-5.

Aghapoor Khameneh, P, Miri Lavasani, S.M, Nabizadeh Nodehi, R, Arjmandi, R, 2019. Water distribution network failure analysis under uncertainty. Int. J. Environ. Sci. Technol. 17 (1), 421–432. https://doi.org/10.1007/s13762-019-02362-y.

Ahiablame, L.M., Engel, B.A., Chaubey, I., 2012. Effectiveness of low impact development practices: literature review and suggestions for future research. Water, Air, Soil Pollut. 223 (7), 4253–4273. https://doi.org/10.1007/s11270-012-1189-2.

Alegre, H., Coelho, S.T., 2012. Infrastructure asset management of urban water systems. Water Supply System Analysis - Selected Topics. https://doi.org/10.5772/52377.

Aliee, H., Zarandi, H.R., 2013. A fast and accurate fault tree analysis based on stochastic logic implemented on field-programmable gate arrays. IEEE Trans. Reliab. 62 (1), 13–22. https://doi.org/10.1109/TR.2012.2221012.

Andenæs, E., Kvande, T., Muthanna, T., Lohne, J., 2018. Performance of blue-green roofs in cold climates: a scoping review. Buildings 8 (4). https://doi.org/10.3390/buildings8040055.

Andenæs, E., Time, B., Muthanna, T., Asphaug, S., Kvande, T., 2021. Risk reduction framework for blue-green roofs. Buildings 11 (5). https://doi.org/10.3390/buildings11050185.

Bahrami, M., Bozorg-Haddad, O., Loáiciga, H.A., 2019. Optimizing stormwater low-impact development strategies in an urban watershed considering sensitivity and uncertainty. Environ. Monit. Assess. 191 (6), 340. https://doi.org/10.1007/s10661-019-7488-y.

Bąk, J., Barjenbruch, M., 2022. Benefits, inconveniences, and facilities of the application of rain gardens in urban spaces from the perspective of climate change—A review. Water 14 (7). https://doi.org/10.3390/w14071153.

Beresh, R., Ciufo, J., Anders, G., 2008. Basic fault tree analysis for use in protection reliability. Int. J. Reliab. Saf. 2 (1–2), 64–78.

Berland, A., Shiflett, S.A., Shuster, W.D., Garmestani, A.S., Goddard, H.C., Herrmann, D. L., Hopton, M.E., 2017. The role of trees in urban stormwater management. Landsc. Urban Plan. 162, 167–177. https://doi.org/10.1016/j.landurbplan.2017.02.017.

Blecken, G.-T., Hunt, W.F., Al-Rubaei, A.M., Viklander, M., Lord, W.G., 2015. Stormwater control measure (SCM) maintenance considerations to ensure designed functionality. Urban Water J. 14 (3), 278–290. https://doi.org/10.1080/1573062x.2015.1111913.

Bouchard, N.R., Osmond, D.L., Winston, R.J., Hunt, W.F., 2013. The capacity of roadside vegetated filter strips and swales to sequester carbon. Ecol. Eng. 54, 227–232. https://doi.org/10.1016/j.ecoleng.2013.01.018.

Braskerud, B.C., Paus, K.H., 2022. Retention of snowmelt and rain from extensive green roofs during snow-covered periods. Blue-Green Syst. 4 (2), 184–196. https://doi.org/10.2166/bgs.2022.011.

Butler, D., Digman, C.J., Makropoulos, C., Davies, J.W., 2018. Urban Drainage, fourth ed. CRC Press. https://doi.org/10.1201/9781351174305.

Caparrós-Martínez, J.L., Milán-García, J., Rueda-López, N., de Pablo-Valenciano, J., 2020. Green infrastructure and water: an analysis of global research. Water 12 (6), 1760. https://www.mdpi.com/2073-4441/12/6/1760.

Cascone, S., 2019. Green roof design: state of the art on technology and materials. Sustainability 11 (11). https://doi.org/10.3390/su11113020.

Cherqui, F., Szota, C., James, R., Poelsma, P., Perigaud, T., Burns, M.J., Fletcher, T.D., Bertrand-Krajewski, J.-L., 2019a. Toward Proactive Management of Stormwater Control Measures Using Low-Cost Technology. Novatech.

Cherqui, F., Szota, C., Poelsma, P., James, R., Burns, M.J., Fletcher, T.D., Bertrand-Krajewski, J.-L., 2019b. How to manage nature-based solution assets such as stormwater control measures?. In: 8th Leading-Edge Conf. on Strategic Asset Management-LESAM.

Cossais, N., Thomas, A.O., Cherqui, F., Morison, P., Bos, D., Martouzet, D., Sibeud, E., Rivière-Honegger, A., Lavau, S., Fletcher, T., 2017. Understanding the challenges of managing SUDS to maintain or improve their performance over time. In: 14th International Conference on Urban Drainage.

Cunningham, A., Colibaba, A., Hellberg, B., Roberts, G.S., Symcock, R., Vigar, N. and Woortman, W. (2017). Stormwater management devices in the Auckland region. Auckland Council Guideline Document, GD2017/00.

Dagenais, D., Brisson, J., Fletcher, T.D., 2018. The role of plants in bioretention systems; does the science underpin current guidance? Ecol. Eng. 120, 532–545. https://doi.org/10.1016/j.ecoleng.2018.07.007.

Delgrosso, Z.L., Hodges, C.C., Dymond, R.L., 2019. Identifying key factors for implementation and maintenance of green stormwater infrastructure. J. Sustain. Water Built Environ. 5 (3), 05019002 https://doi.org/10.1061/jswbay.0000878.

Ding, N., Hamel, P., Zhu, Q., Cherqui, F., & Bertrand-Krajewski, J.-L. (2023). Performance Assessment of Low-cost Water Level Sensor for Water Sensitive Urban Design (WSUD) monitoring in the Tropics Évaluation des performances d'un capteur de niveau d'eau à faible coût pour la surveillance des ouvrages de gestion des eaux pluviales à la source (WSUD) sous les tropiques. Novatech 2023, Lyon, France.

Drake, J., Bradford, A., 2013. Assessing the potential for restoration of surface permeability for permeable pavements through maintenance. Water Sci. Technol. 68 (9), 1950–1958. https://doi.org/10.2166/wst.2013.450.

Ekka, S.A., Rujner, H., Leonhardt, G., Blecken, G.T., Viklander, M., Hunt, W.F., 2021. Next generation swale design for stormwater runoff treatment: a comprehensive approach. J. Environ. Manag. 279, 111756 https://doi.org/10.1016/j.jenvman.2020.111756.

European Commission, 2021. Evaluating the Impact of Nature-Based Solutions: A Handbook for Practitioners. Publications Office of the European Union. https://doi.org/10.2777/244577.

Ferrans, P., Torres, M.N., Temprano, J., Sánchez, J.P.R., 2022. Sustainable urban drainage system (SUDS) modeling supporting decision-making: a systematic quantitative review. Sci. Total Environ. 806, 150447.

Filazzola, A., Shrestha, N., MacIvor, J.S., 2019. The contribution of constructed green infrastructure to urban biodiversity: a synthesis and meta-analysis. J. Appl. Ecol. 56 (9), 2131–2143. https://doi.org/10.1111/1365-2664.13475.

Flanagan, K., Branchu, P., Boudahmane, L., Caupos, E., Demare, D., Deshayes, S., Dubois, P., Meffray, L., Partibane, C., Saad, M., Gromaire, M.-C., 2019. Retention and transport processes of particulate and dissolved micropollutants in stormwater biofilters treating road runoff. Sci. Total Environ. 656, 1178–1190. https://doi.org/10.1016/j.scitotenv.2018.11.304.

Fletcher, T.D., Andrieu, H., Hamel, P., 2013. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: a state of the art. Adv. Water Resour. 51, 261–279. https://doi.org/10.1016/j.advwatres.2012.09.001.

Fletcher, T.D., Shuster, W., Hunt, W.F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P.S., Rivard, G., Uhl, M., Dagenais, D., Viklander, M., 2014. SUDS, LID, BMPs, WSUD and more—The evolution and application of terminology surrounding urban drainage. Urban Water J. 12 (7), 525–542. https://doi.org/10.1080/1573062x.2014.916314.

Fowler, H.J., Wasko, C., Prein, A.F., 2021. Intensification of short-duration rainfall extremes and implications for flood risk: current state of the art and future directions. Philos. Trans. R. Soc. A 379 (2195), 20190541. https://doi.org/10.1098/rsta.2019.0541.

Fu, X., Hopton, M.E., Wang, X., 2021. Assessment of green infrastructure performance through an urban resilience lens. J. Clean. Prod. 289 https://doi.org/10.1016/j.jclepro.2020.125146.

Garmendia, E., Apostolopoulou, E., Adams, W.M., Bormpoudakis, D., 2016. Biodiversity and green infrastructure in Europe: boundary object or ecological trap? Land Policy 56, 315–319. https://doi.org/10.1016/j.landusepol.2016.04.003.

Ghodsi, S.H., Zhu, Z., Matott, L.S., Rabideau, A.J., Torres, M.N., 2023. Optimal siting of rainwater harvesting systems for reducing combined sewer overflows at city scale. Water Res. 230, 119533 https://doi.org/10.1016/j.watres.2022.119533.

Gonzalez-Merchan, C., Barraud, S., Le Coustumer, S., Fletcher, T., 2012. Monitoring of clogging evolution in the stormwater infiltration system and determinant factors. Eur. J. Environ. Civ. Eng. 16 (sup1), s34–s47. https://doi.org/10.1080/19648189.2012.682457.

Gunawardena, K.R., Wells, M.J., Kershaw, T., 2017. Utilising green and bluespace to mitigate urban heat island intensity. Sci. Total Environ. 584–585, 1040–1055. https://doi.org/10.1016/j.scitotenv.2017.01.158.

Hansen, R., Frantzeskaki, N., McPhearson, T., Rall, E., Kabisch, N., Kaczorowska, A., Kain, J.-H., Artmann, M., Pauleit, S., 2015. The uptake of the ecosystem services concept in planning discourses of European and American cities. Ecosyst. Serv. 12, 228–246. https://doi.org/10.1016/j.ecoser.2014.11.013.

Homet, K., Kremer, P., Smith, V., Ampomah, R., Strader, S.M., 2022. Mapping predicted areas of common maintenance impacts to green stormwater infrastructure in Philadelphia, Pennsylvania. J. Sustain. Water Built Environ. 8 (3) https://doi.org/10.1061/jswbay.0000986.

Hoover, F.-A., Meerow, S., Coleman, E., Grabowski, Z., McPhearson, T., 2023. Why go green? Comparing rationales and planning criteria for green infrastructure in U.S. city plans. Landsc. Urban Plan. 237 https://doi.org/10.1016/j.landurbplan.2023.104781.

Jia, H., Liu, Z., Xu, C., Chen, Z., Zhang, X., Xia, J., Yu, S.L., 2022. Adaptive pressure-driven multi-criteria spatial decision-making for a targeted placement of green and grey runoff control infrastructures. Water Res. 212, 118126 https://doi.org/10.1016/j.watres.2022.118126.

Kabir, S., 2017. An overview of fault tree analysis and its application in model based dependability analysis. Expert Syst. Appl. 77, 114–135. https://doi.org/10.1016/j.eswa.2017.01.058.

Kabisch, N., Qureshi, S., Haase, D., 2015. Human–environment interactions in urban green spaces—A systematic review of contemporary issues and prospects for future research. Environ. Impact Assess. Rev. 50, 25–34. https://doi.org/10.1016/j.eiar.2014.08.007.

Kasprzyk, M., Szpakowski, W., Poznanska, E., Boogaard, F.C., Bobkowska, K., Gajewska, M., 2022. Technical solutions and benefits of introducing rain gardens—Gdansk case study. Sci. Total Environ. 835, 155487 https://doi.org/10.1016/j.scitotenv.2022.155487.

Kavehei, E., Jenkins, G.A., Adame, M.F., Lemckert, C., 2018. Carbon sequestration potential for mitigating the carbon footprint of green stormwater infrastructure. Renew. Sustain. Energy Rev. 94, 1179–1191. https://doi.org/10.1016/j.rser.2018.07.002.

Khodadad, M., Aguilar-Barajas, I., Khan, A.Z., 2023. Green infrastructure for urban flood resilience: a review of recent literature on bibliometrics, methodologies, and typologies. Water 15 (3), 523.

Kondo, M.C., Sharma, R., Plante, A.F., Yang, Y., Burstyn, I., 2016. Elemental concentrations in urban green stormwater infrastructure soils. J. Environ. Qual. 45 (1), 107–118. https://doi.org/10.2134/jeq2014.10.0421.

Kukadia, J., Lundholm, M., Russell, I., 2019. Designing rain gardens: a practical guide. In: Dodd, P. (Ed.), Urban Design London.

Langeveld, J.G., Cherqui, F., Tscheikner-Gratl, F., Muthanna, T.M., Juarez, M.F.-D, Leitão, J.P, Roghani, B, Kerres, K, do Céu Almeida, M, Werey, C, Rulleau, B, 2022. Asset management for blue-green infrastructures: a scoping review. Blue-Green Syst. 4 (2), 272–290. https://doi.org/10.2166/bgs.2022.019.

Le Coent, P., Graveline, N., Altamirano, M.A., Arfaoui, N., Benitez-Avila, C., Biffin, T., Calatrava, J., Dartee, K., Douai, A., Gnonlonfin, A., Hérivaux, C., Marchal, R., Moncoulon, D., Piton, G, 2021. Is-it worth investing in NBS aiming at reducing water risks? Insights from the economic assessment of three European case studies. Nature-Based Solutions 1. https://doi.org/10.1016/j.nbsj.2021.100002.

Le Gauffre, P., Cherqui, F., 2009. Sewer rehabilitation criteria evaluated by fusion of fuzzy indicators. In: LESAM 2009.

Li, Y., Babcock Jr., R.W., 2014. Green roof hydrologic performance and modeling: a review. Water Sci. Technol. 69 (4), 727–738. https://doi.org/10.2166/wst.2013.770.

Lindhe, A., Norberg, T., Rosén, L., 2012. Approximate dynamic fault tree calculations for modelling water supply risks. Reliab. Eng. Syst. Saf. 106, 61–71. https://doi.org/10.1016/j.ress.2012.05.003.

Masalegooyan, Z., Piadeh, F., Behzadian, K., 2022. A comprehensive framework for risk probability assessment of landfill fire incidents using fuzzy fault tree analysis. Process Saf. Environ. Prot. 163, 679–693.

Melbourne Water. (2013). *WSUD maintenance guidelines - A guide for asset managers*. https://www.melbournewater.com.au/media/636/download.

Mendez, C.B., Klenzendorf, J.B., Afshar, B.R., Simmons, M.T., Barrett, M.E., Kinney, K.A., Kirisits, M.J., 2011. The effect of roofing material on the quality of harvested rainwater. Water Res. 45 (5), 2049–2059. https://doi.org/10.1016/j.watres.2010.12.015.

Minnesota Pollution Control Agency (2023). *Minnesota Stormwater Manual*. Retrieved July 25 from https://stormwater.pca.state.mn.us/index.php?title=Main_Page.

Mohsen Hassan Abdalla, E., Alfredsen, K, Merete Muthanna, T, 2022. Towards improving the calibration practice of conceptual hydrological models of extensive green roofs. J. Hydrol. 607, 127548 https://doi.org/10.1016/j.jhydrol.2022.127548.

Moore, T.L., Gulliver, J.S., Stack, L., Simpson, M.H., 2016. Stormwater management and climate change: vulnerability and capacity for adaptation in urban and suburban contexts. Clim. Change 138, 491–504.

Moura, N.C.B., Pellegrino, P.R.M., Martins, J.R.S., 2016. Best management practices as an alternative for flood and urban storm water control in a changing climate. J. Flood Risk Manag. 9 (3), 243–254. https://doi.org/10.1111/jfr3.12194.

Müller, A., Österlund, H., Marsalek, J., Viklander, M., 2020. The pollution conveyed by urban runoff: a review of sources. Sci. Total Environ. 709, 136125 https://doi.org/10.1016/j.scitotenv.2019.136125.

Nazarpour, S., Gnecco, I., Palla, A., 2023. Evaluating the effectiveness of bioretention cells for urban stormwater management: a systematic review. Water 15 (5). https://doi.org/10.3390/w15050913.

Ong, N.A.F.M.N., Sadiq, M.A., Said, M.S.M., Jomaas, G., Tohir, M.Z.M., Kristensen, J.S., 2022. Fault tree analysis of fires on rooftops with photovoltaic systems. J. Build. Eng. 46, 103752.

Parsons, D., 2010. Regulating asset management through serviceability and a common framework for investment planning. Definitions, Concepts and Scope of Engineering Asset Management Review, vol 1. Springer, London, pp. 65–93. https://doi.org/10.1007/978-1-84996-178-3_4.

Pérez, A.I.N., Ugarelli, R., 2014. Fault tree analysis as a tool for risk assessment and its use for infrastructure asset management in water utilities. VANN 49 (4), 492–499.

Pons, V., Abdalla, E.M.H., Tscheikner-Gratl, F., Alfredsen, K., Sivertsen, E., Bertrand-Krajewski, J.-L., Muthanna, T.M., 2023. Practice makes the model: a critical review of stormwater green infrastructure modelling practice. Water Res. 236, 119958 https://doi.org/10.1016/j.watres.2023.119958.

Probst, N., Bach, P.M., Cook, L.M., Maurer, M., Leitão, J.P., 2022. Blue green systems for urban heat mitigation: mechanisms, effectiveness and research directions. Blue-Green Syst. 4 (2), 348–376. https://doi.org/10.2166/bgs.2022.028.

Rasul, M.G., Arutla, L.K.R., 2020. Environmental impact assessment of green roofs using life cycle assessment. Energy Reports 6, 503–508. https://doi.org/10.1016/j.egyr.2019.09.015.

Ren, H., Chen, X., Chen, Y., 2017. Fault tree analysis for composite structural damage. Reliability Based Aircraft Maintenance Optimization Applications, pp. 115–131. https://doi.org/10.1177/0954410013493229.

Riva, F., Fahrig, L., 2023. Obstruction of biodiversity conservation by minimum patch size criteria. Conserv. Biol. https://doi.org/10.1111/cobi.14092.

Robinson, T., Schulte-Herbrüggen, H., Mácsik, J., Andersson, J., 2019. Raingardens for Stormwater Management: Potential of Raingardens in a Nordic Climate. Trafikverket.

Roghani, B., Bahrami, M., Rokstad, M.M., Cherqui, F., Muthanna, T., Tscheikner-Gratl, F., 2023. Performance assessment indicators for green infrastructures: a comparison between international guidelines Indicateurs d'évaluation de la performance des infrastructures vertes: comparaison des directives internationales. In: Novatech 2023 11e Conférence Internationale sur l'Eau dans la Ville. Lyon, France.

Rowe, D.B., 2011. Green roofs as a means of pollution abatement. Environ. Pollut. 159 (8–9), 2100–2110. https://doi.org/10.1016/j.envpol.2010.10.029.

Ruijters, E., Stoelinga, M., 2015. Fault tree analysis: a survey of the state-of-the-art in modeling, analysis and tools. Comput. Sci. Rev. 15–16, 29–62. https://doi.org/10.1016/j.cosrev.2015.03.001.

Sadiq, R., Saint-Martin, E., Kleiner, Y., 2008. Predicting risk of water quality failures in distribution networks under uncertainties using fault-tree analysis. Urban Water J. 5 (4), 287–304. https://doi.org/10.1080/15730620802213504.

Sañudo-Fontaneda, L.A., Roces-García, J., Coupe, S.J., Barrios-Crespo, E., Rey-Mahía, C., Álvarez-Rabanal, F.P., Lashford, C., 2020. Descriptive analysis of the performance of a vegetated swale through long-term hydrological monitoring: a case study from Coventry, UK. Water 12 (10). https://doi.org/10.3390/w12102781.

Scolaro, T.P., Ghisi, E., 2022. Life cycle assessment of green roofs: a literature review of layers materials and purposes. Sci. Total Environ. 829, 154650 https://doi.org/10.1016/j.scitotenv.2022.154650.

Shafique, M., Kim, R., Kyung-Ho, K, 2018a. Evaluating the capability of grass swale for the rainfall runoff reduction from an urban parking lot, Seoul, Korea. Int. J. Environ. Res. Public Health 15 (3). https://doi.org/10.3390/ijerph15030537.

Shafique, M., Kim, R., Rafiq, M., 2018b. Green roof benefits, opportunities and challenges—A review. Renew. Sustain. Energy Rev. 90, 757–773. https://doi.org/10.1016/j.rser.2018.04.006.

Shahzad, H., Myers, B., Boland, J., Hewa, G., Johnson, T., 2022. Stormwater runoff reduction benefits of distributed curbside infiltration devices in an urban catchment. Water Res. 215, 118273 https://doi.org/10.1016/j.watres.2022.118273.

Shannon, T.P., Ahler, S.J., Mathers, A., Ziter, C.D., Dugan, H.A., 2020. Road salt impact on soil electrical conductivity across an urban landscape. J. Urban Ecol. 6 (1) https://doi.org/10.1093/jue/juaa006.

Silva, C.M., Flores-Colen, I., Coelho, A., 2015. Green roofs in Mediterranean areas—Survey and maintenance planning. Build. Environ. 94, 131–143. https://doi.org/10.1016/j.buildenv.2015.07.029.

Skrede, T.I., Muthanna, T.M., Alfredesen, K., 2020. Applicability of urban streets as temporary open floodways. Hydrol. Res. 51 (4), 621–634. https://doi.org/10.2166/nh.2020.067.

Smith, V.B., McGauley, M.W., Newman, M., Garzio-Hadzick, A., Kurzweil, A., Wadzuk, B. M., Traver, R., 2023. A relational data model for advancing stormwater infrastructure management. J. Sustain. Water Built Environ. 9 (1) https://doi.org/10.1061/jswbay.Sweng-478.

Spalanzani, W., Ciptomulyono, U., Suef, M., Asmuddin, Salwiah, 2020. Fault tree and decision making trial and evaluation laboratory model for formulating risk mitigation strategies at water production process of PDAM Baubau. AIP Conf. Proc. 2217 (1) https://doi.org/10.1063/5.0000750.

Stagge, J.H., Davis, A.P., Jamil, E., Kim, H., 2012. Performance of grass swales for improving water quality from highway runoff. Water Res. 46 (20), 6731–6742. https://doi.org/10.1016/j.watres.2012.02.037.

ten Veldhuis, J.A.E., Clemens, F.H.L.R., van Gelder, P.H.A.J.M., 2011. Quantitative fault tree analysis for urban water infrastructure flooding. Struct. Infrastruct. Eng. 7 (11), 809–821. https://doi.org/10.1080/15732470902985876.

Tetra Tech, 2016. Operation and Maintenance of Green Infrastructure Receiving Runoff from Roads and Parking Lots. Environmental Protection Agency Great Lakes National Program Office.

Thurston, R.A. (2017). *Defining And Measuring Green Roof Failure Using A Case Study Of Incentivized Industrial, Commercial, And Institutional Vegetated Roofs In Portland, Oregon*.

Tolderlund, L., 2010. Design guidelines and maintenance manual for green roofs in the semi-arid and arid west. Green Roofs for Healthy Cities Denver. Colorado State University.

Tomson, M., Kumar, P., Barwise, Y., Perez, P., Forehead, H., French, K., Morawska, L., Watts, J.F., 2021. Green infrastructure for air quality improvement in street canyons. Environ. Int. 146, 106288 https://doi.org/10.1016/j.envint.2020.106288.

Toronto and Region Conservation Authority (TRCA), 2016. Low impact development stormwater management practice inspection and maintenance guide. In: Prepared by the Sustainable Technologies Evaluation Program. Vaughan, Ontario.

USEPA, 2021. NPDES: Stormwater Best Management Practices Fact Sheets. Retrieved July 25 from. https://www.epa.gov/npdes/national-menu-best-management-practices-bmps-stormwater-post-construction.

Vijayaraghavan, K., 2016. Green roofs: a critical review on the role of components, benefits, limitations and trends. Renew. Sustain. Energy Rev. 57, 740–752. https://doi.org/10.1016/j.rser.2015.12.119.

Vijayaraghavan, K., Raja, F.D., 2014. Design and development of green roof substrate to improve runoff water quality: plant growth experiments and adsorption. Water Res. 63, 94–101. https://doi.org/10.1016/j.watres.2014.06.012.

Viñas, V., Sokolova, E., Malm, A., Bergstedt, O., Pettersson, T.J., 2022. Cross-connections in drinking water distribution networks: quantitative microbial risk assessment in combination with fault tree analysis and hydraulic modelling. Sci. Total Environ. 831, 154874.

Vollaers, V., Nieuwenhuis, E., van de Ven, F., Langeveld, J., 2021. Root causes of failures in sustainable urban drainage systems (SUDS): an exploratory study in 11 municipalities in The Netherlands. Blue-Green Syst. 3 (1), 31–48. https://doi.org/10.2166/bgs.2021.002.

Wagner, T.V., Rempe, F., Hoek, M., Schuman, E., Langenhoff, A., 2023. Key constructed wetland design features for maximized micropollutant removal from treated municipal wastewater: a literature study based on 16 indicator micropollutants. Water Res. 244, 120534 https://doi.org/10.1016/j.watres.2023.120534.

Wang, M., Liu, M., Zhang, D., Qi, J., Fu, W., Zhang, Y., Rao, Q., Bakhshipour, A.E., Tan, S. K., 2023. Assessing and optimizing the hydrological performance of grey–green infrastructure systems in response to climate change and non-stationary time series. Water Res. 232, 119720 https://doi.org/10.1016/j.watres.2023.119720.

Wang, M., Zhang, D., Wang, Z., Zhou, S., Tan, S.K., 2021. Long-term performance of bioretention systems in storm runoff management under climate change and life-cycle condition. Sustain. Cities Soc. 65, 102598 https://doi.org/10.1016/j.scs.2020.102598.

Water Environment Federation. (2022). Urban Stormwater Controls Operation and Maintenance. 1.

Whitford, V., Ennos, A.R., Handley, J.F., 2001. City form and natural process"—Indicators for the ecological performance of urban areas and their application to Merseyside, UK. Landsc. Urban Plan. 57 (2), 91–103. https://doi.org/10.1016/S0169-2046(01)00192-X.

Winston, R.J., Davidson-Bennett, K.M., Buccier, K.M., Hunt, W.F., 2016. Seasonal variability in stormwater quality treatment of permeable pavements situated over heavy clay and in a cold climate. Water, Air, Soil Pollut. 227 (5), 140. https://doi.org/10.1007/s11270-016-2839-6.

Wu, W., Jamali, B., Zhang, K., Marshall, L., Deletic, A., 2023. Water sensitive urban design (WSUD) spatial prioritisation through global sensitivity analysis for effective urban pluvial flood mitigation. Water Res. 235, 119888 https://doi.org/10.1016/j.watres.2023.119888.

Xing, Y., Jones, P., Donnison, I., 2017. Characterisation of nature-based solutions for the built environment. Sustainability 9 (1). https://doi.org/10.3390/su9010149.

Yazdi, M., Kabir, S., Walker, M., 2019. Uncertainty handling in fault tree based risk assessment: state of the art and future perspectives. Process Saf. Environ. Prot. 131, 89–104. https://doi.org/10.1016/j.psep.2019.09.003.

Yazdi, M., Mohammadpour, J., Li, H., Huang, H.Z., Zarei, E., Pirbalouti, R.G., Adumene, S., 2023. Fault tree analysis improvements: a bibliometric analysis and literature review. Qual. Reliab. Eng. Int. 39 (5), 1639–1659.