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Research article

# Maintenance matters: Insights from guidelines and practice on nature-based stormwater solutions

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ABSTRACT

Nature-based stormwater solutions (NBSS) support urban stormwater management while providing additional ecosystem services. Their hybrid grey–green design sets them apart from conventional drainage systems requiring specific maintenance to ensure long-term performance. This study combines a global practitioner survey and a review of maintenance guidelines aiming to characterize shortcomings in NBSS management, focusing on failure mechanisms and maintenance practices. Based on 22 responses, survey results show that, in the absence of maintenance, systems are mainly affected by sediment buildup, litter, and green waste accumulation, as well as excessive vegetation growth, and invasive species. Maintenance (e.g., visual inspections, litter removal) is performed regularly, from monthly to annually, consistent with guidelines. Vegetation management typically follows a seasonal frequency (~three months). Our review of 35 guidelines indicates that maintenance practices are very diverse and context-dependent, depending on the type of NBSS and socio-ecological-technological context, reflecting a potential barrier to mainstreaming of best practices. No universal maintenance frequency can be established as it strongly depends on NBBS and local context (e.g., climate, available resources). Systematic data collection on failures, their occurrence, and impacts is however essential to support predictive local maintenance strategy.

## 1. Introduction

Motivated by a desire to minimise impacts on receiving waters, as well as the need to improve the amenity of the urban environment, particularly in response to densification and climate change, cities around the world are increasingly adopting nature-based stormwater solutions (NBSS) (Flynn and Davidson, 2016; Helness and Sivertsen, 2025). These systems typically combine vegetation and soil or filter media to filter, detain and retain stormwater, both to improve its quality and decrease peak flow to deliver a more natural flow regime. While the technology around NBSS continues to evolve, multiple authors have identified that the limiting factors in their application are no longer solely linked to their design (Vollaers et al., 2021; Kaur et al., 2025). More specifically, Kaur et al. (2025) highlight that failures arising from

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human actions post-implementation or from external pressures during the operation and maintenance (O&M) phase can often be classified as preventable, emphasizing the critical role of systematic maintenance planning.

Such planning is most effective when grounded in data on failures and maintenance practices that accurately capture how these systems evolve over time. This data would also be valuable for incorporating into existing models, which currently only rarely account for failure and maintenance but for which they may influence long-term performance (Bergman et al., 2011; Funke and Kleidorfer, 2024). In response to concerns about this limitation, several authors have begun to investigate the barriers facing long-term O&M (Harvey et al., 2009; Gerlak et al., 2022; Langeveld et al., 2022; Knapik et al., 2025; Kaur et al., 2025). Broadly, these challenges fall into four categories specific to NBSS.

1. Their complex nature,
2. Their distributed implementation,
3. Their unclear and blurry governance and,
4. Their cost and long-term funding uncertainty.

NBSS are inherently more complex systems than typical grey infrastructure (e.g., channels, pipes, pits, detention basins). They comprise a greater number of components, many of which interact within the system, and therefore require a broader range of skills—and equipment—to ensure effective maintenance. These components include hydraulic elements (e.g., inlets, outlets, overflow and diversion structures, underdrains), vegetative elements (e.g., planted species as well as naturally colonising vegetation, including weeds), substrate elements (e.g., filter media and accumulated influent sediments that may form clogging layers), and aesthetic or recreational features (e.g., walking paths, viewing platforms). Each of these elements can experience different types of failure (Bahrami et al., 2024; Almasalmeh et al., 2026), meaning that overall system performance depends on their interactions and the combinations of potential failure modes. However, the interactions among these elements also contribute to the multifunctionality of NBSS and support their capacity to provide a wide range of services (Belmeziti et al., 2015).

In addition, the distributed nature of NBSS is fundamental to their design, as they are typically implemented as close as possible to the source of runoff in order to reduce catchment size and flow rates. However, this spatial distribution introduces additional layers of interaction within an already complex system. It also has implications for maintenance, as teams must service numerous dispersed assets, potentially increasing overall costs (Knapik et al., 2025). Currently, there is a lack of long-term data on maintenance costs which are most often estimated as a proportion of capital or construction costs (Schriner, 2018; Liu et al., 2020). This complicates the necessary funding and asset management planning.

The long-term maintenance of distributed systems is further complicated by uncertainties around asset management planning and sustained funding. In many jurisdictions, securing funding for the construction of NBSS is considerably easier than obtaining support for their ongoing maintenance (Qiao et al., 2019). This may reflect the use of different funding streams, or the fact that maintenance is often less visible and less politically attractive than investing in new projects. In addition, further costs frequently arise after implementation as unforeseen issues and challenges emerge, underscoring the importance of maintenance expertise and its early integration into the planning process (Moin et al., 2022). Ultimately, effective maintenance relies on well-funded, adequately resourced, multidisciplinary teams; however, given these complexities, many NBSS owners struggle to establish and sustain such teams (Cossais, 2021).

Although these challenges are relatively well documented, existing perspectives are often confined to specific local contexts and more focused on identifying problems than on describing typical practices at a global scale. Given this context, we sought to better understand the maintenance practices commonly implemented by NBSS owners worldwide, as well as the types and frequency of system failures. Previous survey- and interview-based studies conducted in countries such as the United States, Canada, Australia, and France provide valuable insights (Erickson et al., 2010; Jean et al., 2022), but they typically targeted predefined respondent groups. In contrast, our approach aimed to reach a broader audience without restricting the participant profile.

The objective of this study is to contribute to a better understanding of how to support effective ongoing O&M of NBSS informed first and foremost by the experience of practitioners themselves (i.e., those who actually oversee the maintenance of NBSS). To achieve this, we: (i) conducted an international survey targeting 17 countries to assess current practices and the main causes of failure; and (ii) reviewed a range of NBSS guidelines to compare with the survey findings and identify key maintenance recommendations for practitioners. For the sake of clarity, the term NBSS is used throughout this article to refer to nature-based solutions managing stormwater either by infiltration or retention.

## 2. Methodology

### 2.1. Survey

In an initial pilot version, the international survey was created by adapting a French survey we had previously disseminated in April 2024 among 21 practitioners, focusing on maintenance practices and failures occurrences, as well as contributing failure factors. The principal finding of that survey was that the primary identified causes of NBSS failure were linked to socio-institutional aspects, such as the need to improve the efficiency of maintenance activities, the lack of communication between the different departments, and the lack of training of maintenance personnel (Girot et al., 2025a). This result is aligned with findings from Vollaers et al. (2021) that root causes for failure are linked to management shortcomings resulting from shared responsibility. In addition, lack of knowledge remains an important concern.

Prompted by this gap and adopting a more technical perspective for this international survey, we aimed both to examine the failure mechanisms impacting NBSS throughout their O&M and to gain insight into maintenance strategies. Consequently, the survey was structured into two main sections, each targeting one of the specific objectives. Selected NBSS for this study were bioretention/rain gardens, vegetated swales, constructed stormwater wetlands, infiltration basins, wet retention ponds and dry detention basins. We chose to consider only NBSS with significant vegetation potential (excluding permeable pavements or drainage trenches), implemented at ground level in urban spaces and greater than 2 $m^2$ (excluding green roofs, green walls and tree pits) and therefore relying on interactions between vegetation, soil, and stormwater. These six typologies are commonly found in the literature and are typically categorized into either infiltration-based or retention-based solutions ((Hoban, 2019; Eisenberg et al., 2022; Palermo et al., 2023). Respondents were asked to provide answers for each section with respect to a specific NBSS, which did not have to be the same for both sections (Appendix A). Closed-ended questions were employed to enhance response rates, while open-ended questions were incorporated to capture additional insights that may not have been anticipated.

The first section of the survey focused on failure rates and impacts for nine failure types, selected from the fault-tree analysis presented by Bahrami et al. (2024). Only failures linked to O&M were chosen.

- Five failures linked to mulch and vegetation evolution in the NBSS: unhealthy vegetation, overly dense vegetation, invasive plants taking over, green waste accumulation, mulch accumulation.
- Four failures linked to human activities in the drainage basin: trash accumulation, vandalism, sediment accumulation, winter road maintenance.

Respondents were first asked to select a specific NBSS among the

above list for which they have the most experience, regarding failure type and frequency. For each listed failure, respondents were asked to indicate which system component(s) is affected, among the following.

- the inlet(s) or pretreatment device(s),
- the outlet(s) or overflow device(s),
- the main channel or ponding area.

In addition to identifying the affected component, respondents were asked to indicate the likelihood of the failure occurring in the absence of maintenance, and the required urgency of maintenance, ranging from immediate (within the next few days) to none (until the next scheduled maintenance visit).

The second section of the survey focused on the maintenance strategies adopted by practitioners. It first addressed NBSS governance, including the departments involved and the number of actors participating in maintenance activities, as well as reporting practices and the use of legal frameworks. No specific type of legal framework was imposed; this question was intentionally left open-ended to allow respondents to interpret it according to their professional background, discipline, and operational context.

In addition, a list of maintenance practices - derived from a review of O&M guidelines (Appendix B) - was provided to respondents. They were asked to select the practices relevant to their context and indicate their corresponding frequency of implementation. To cover a sufficiently large scope, the list included both routine and non-periodic practices, as well as complete replacement (Table 1). Here again, respondents were asked to detail the maintenance practices and their frequency of practice for a specific NBSS of their choice, for which they have the most experience on its maintenance strategy. Response options for routine practices ranged from monthly to once every two or more years, while occasional practices were assigned frequencies from once a year to once every ten or more years. Additional options included 'I don't know,' 'Never,' and 'Not applicable to the selected NBSS,' along with an open field for respondents to specify frequencies not listed.

The first version of the survey was then presented and shared as a document to a working group of 11 researchers from universities across Europe, Canada, Australia and South East Asia. Feedback from the working group was made on the shared document. Three key contributions emerged: (i) the addition of preliminary background questions, such as the types of departments involved in NBSS maintenance and the age range of the NBSS solutions; (ii) the decision to allow different NBSS to be considered in each section, acknowledging that respondents may have varying experiences with failures and maintenance practices; and (iii) the selection of malfunctions based on the three system components.

Once the final English version of the survey was agreed upon (Appendix A), translations in the 9 languages represented in the working group were undertaken, to ensure local terminology was used (noting that in the field of NBSS, there is a tendency for very local terminology, which changes from place to place and even changes over time) (Fletcher et al., 2015). The English version targeted Australia, Canada, the United Kingdom, and the United States. The German version was distributed in Austria and Germany, while the French version targeted France and Québec (Canada). Other translations included Estonian (Estonia), Italian (Italy), Dutch (the Netherlands and Belgium), Norwegian (Norway, also understandable in Sweden and Denmark), Mandarin (China), and Indonesian (Indonesia). All nine versions of the survey were integrated on the online survey platform.

The survey dissemination began in mid-December 2024 with a LinkedIn post, shared by the working group. During January and February 2025, it was further distributed through the researchers' personal networks as well as national networks, and broader international networks, including the Joint Committee of Urban Drainage (JCUD) and the European Water Association (EWA). A second dissemination phase, following the same approach, was conducted in April 2025. The survey was closed in September 2025 to begin analysis of the results.

The survey results were analysed according to the two main sections. The first focused on failures, examined by NBSS component and NBSS type. The second addressed maintenance, beginning with governance aspects—namely the number and types of departments involved, reporting practices, and the legal framework—followed by an analysis of maintenance practices, presented by frequency for each NBSS type.

**Table 1**
List of maintenance practices included in the survey based on the action plans concept presented in EN 752 (2017) and adapted to NBSS management with regard to specific actions.

| | | |
|---|---|---|
| **Routine practices** | Inspections practices | Visual inspection, control of animal burrows |
| | Site maintenance | Litter and debris removal |
| | Vegetation maintenance | Vegetation inspection, herbaceous management, shrubs and plants management, tree management |
| | Specific biodiversity-friendly practices | Varied-mowing management, late mowing, leaving dead wood on site, leaving green waste on site, encouraging establishment of spontaneous vegetation, eco-pasture |
| **Occasional practices** | Targeted cleaning, repair and renovation | Pipe cleaning, sediment buildup removal, structural repair, topsoil or filter media replacement, vegetation replacement |
| | Investigation practices/ Measurements | Water quality analysis, soil analysis, infiltration testing |
| **Replacement** | Replacement | Replacement |

### 2.2. Review of current guidelines

To complement the survey results and assess whether operational feedback aligns with recommendations presented in the literature, a review of 35 sources - 33 from grey literature and two from scientific literature (Appendix B) - was conducted to identify commonly reported maintenance practices and their recommended frequencies. The grey literature comprised a book, technical manuals, and design and O&M guidelines, while the scientific sources included a literature review and a conference paper presenting findings from both a literature review and survey data. The selected guidelines covered at least one of the six NBSS examined in the survey. They were drawn either from an up-to-date repository (http://tiny.cc/guidelinesSCMs) or provided through the working group's research network. The sources span the period from 2006 to 2024 and primarily originate from the United States, Canada, Australia, France, the United Kingdom, China, and Singapore. Because such guidelines are typically published in their respective national languages, the review focused mainly on English-language documents, with the exception of materials from China and France, which could be translated by two of the authors. While not exhaustive, this review offers additional context for interpreting the survey results and is therefore presented alongside them.

From the list of maintenance practices included in the survey (Table 1), only the following were considered in the guideline review analysis: inspection, site maintenance, vegetation management, and sediment buildup removal. These were selected because they are the most commonly applied across all NBSS types, and were therefore expected to provide a substantial amount of information to complement the limited survey responses. Similarly to the analysis of the survey results, for each maintenance practice, both the frequency of implementation and the associated NBSS were recorded.

## 3. Results

The online survey was viewed by 1116 unique users during the nine-month period it was open. It was completed by 22 respondents distributed between North America, Australia and Europe. Most responses

originate from countries in which the research group is actively engaged. However, the response rate - less than 2% of the viewers - is considerably low. The collected responses should not be interpreted as a comprehensive representation of current practices worldwide; rather, they provide initial insights that help open the discussion. These insights have been supported by operational literature and, taken together, reflect the most up-to-date information available to our knowledge. The following results cover: (i) observed failures, (ii) maintenance governance, and (iii) maintenance practices.

### 3.1. Observed failures

#### 3.1.1. NBSS with strongest practitioner experience

The spatial distribution of the NBSS for which each respondent had the most experience regarding failure is represented in Fig. 1. Bioretention systems were the most frequently represented NBSS type, accounting for 32% of responses, and were primarily selected by respondents from Australia and North America. This was followed by wet ponds, representing 23% of responses. Swales (18%) and infiltration basins (14%) occupied the third and fourth positions, respectively, and were chosen exclusively by respondents from Western Europe. Lastly, dry detention basins (9%) and constructed stormwater wetlands (5%) were less frequently selected.

The age range of NBSS systems that practitioners are most experienced with regarding failure is between five and 20 years old (Appendix C). No respondents mentioned systems older than 30 years old.

#### 3.1.2. Common failures

As explained in the methodology, respondents selected observed failures according to their impact on the following three main elements of an NBSS, upstream to downstream: its inlet or pretreatment devices, its main channel or ponding area and its outlet or overflow devices. Respondents were asked to assess the likelihood of each failure occurring in the absence of maintenance. Table 2 presents an overview of the most frequently chosen failures per NBSS component. For each failure, the percentage of responses mentioning it was calculated based on the total number of responses reporting at least one failure on the corresponding NBSS component (inlet or pretreatment devices, main channel area and outlet or overflow devices). The impacted NBSS are also specified per failure. The complete responses with responses for all failures are provided in the supplementary material (Appendix D).

Sediment accumulation emerges as a common failure across all three NBSS elements, although it appears particularly significant for inlet and pretreatment devices (69% of responses). The accumulation of trash and green waste is mainly associated with inlets and outlets, where it may obstruct water flow. Green waste accumulation refers both to leaves from surrounding trees or from cuttings from green space maintenance that might have been washed towards the outlet during rainfall events. Stormwater flow through inlets and outlets is also frequently restricted due to overly dense vegetation. Vegetation can also become a source of failure for the main channel area where invasive plants taking over and unhealthy vegetation are common concerns. Their occurrence may impact both the hydraulic function of the solution - runoff reduction and pollutant treatment mechanisms - as well as co-benefits linked to biodiversity and aesthetics. Additionally, a respondent highlighted issues related to rat infestations and the presence of dangerous insects, such as the Asian hornet, which represent more of a risk to human health and well-being.

Given the limited sample size and representative distribution of NBSS types, no statistically robust interpretation regarding failure rates across NBSS categories can be drawn. However, retention systems (e.g., wet ponds and constructed stormwater wetlands) exhibited fewer reported failures affecting the main channel or ponding area than infiltration and detention systems (e.g., swales, bioretention systems, and infiltration and detention basins). One possible explanation relates to the size of the ponding area. Retention systems generally have larger water storage zones than linear systems such as swales, which may delay the onset of visible degradation or reduce the immediate impact of localized failures. Additionally, the presence of a permanent water pool may discourage certain disturbances, such as litter disposal. Another

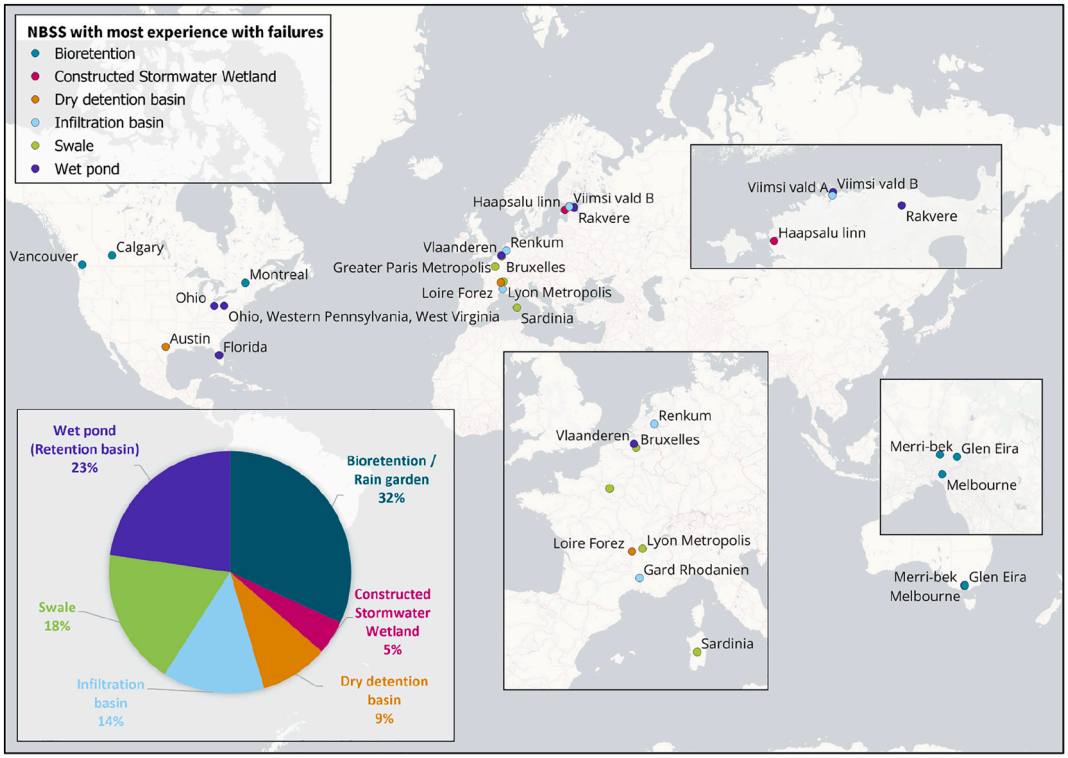



**Fig. 1.** Geographical distribution of NBSS with the most practitioner experience in failures.

**Table 2**
Most frequent failures per NBSS component according to respondents (in the absence of maintenance).

| Impacted NBSS component | Main failure | Number of responses | Perc. of responses | Impacted NBSS | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Bioretention/ Rain garden | Swale | Constructed stormwater wetland | Infiltration basin | Wet retention pond | Dry detention basin |
| Inlet or pretreatment devices | Sediment accumulation | 11 | 69% | X | | | X | X | X |
| | Trash accumulation | 10 | 63% | X | | | X | X | X |
| | Green waste accumulation | 7 | 44% | X | X | | X | X | X |
| | Overly dense vegetation | 7 | 44% | X | X | | X | X | X |
| Main channel or ponding area | Invasive plants taking over | 13 | 81% | X | X | | X | X | X |
| | Overly dense vegetation | 12 | 75% | X | X | | X | X | X |
| | Sediment accumulation | 7 | 44% | X | X | | | X | X |
| | Unhealthy vegetation | 7 | 44% | X | X | | | | X |
| Outlet or overflow devices | Green waste accumulation | 9 | 69% | X | X | X | | X | X |
| | Trash accumulation | 9 | 69% | X | X | | | X | X |
| | Sediment accumulation | 6 | 46% | X | X | X | | X | X |
| | Overly dense vegetation | 5 | 38% | | X | | | X | X |
| | Mulch accumulation | 5 | 38% | X | X | | | | X |

factor may be linked to ecological dynamics, particularly in wetlands. These systems are often expected to self-regulate, and ecological changes - such as shifts in vegetation composition or the presence of invasive species - may not always be perceived as failures, but rather as part of natural ecosystem evolution. Expectations may therefore differ across asset types. For example, swales located along roads and strongly embedded within the urban fabric are subject to higher visual and functional performance standards, as any malfunction can quickly affect both the technical performance and the aesthetics of the surrounding urban environment.

### 3.2. Maintenance governance

#### 3.2.1. Departments involved

In order to capture a comprehensive overview of NBSS maintenance governance, respondents were asked to indicate which of five commonly involved departments - water, drainage, green spaces, road, and cleaning - were represented in their organization. An open option was included to nominate other relevant departments. Up to eleven different department types were identified as being involved in NBSS maintenance across the 22 responses (Fig. 2). This finding highlights the diversity of perspectives, disciplinary backgrounds, knowledge bases, working methods, and scopes of intervention through which NBSS maintenance is addressed.

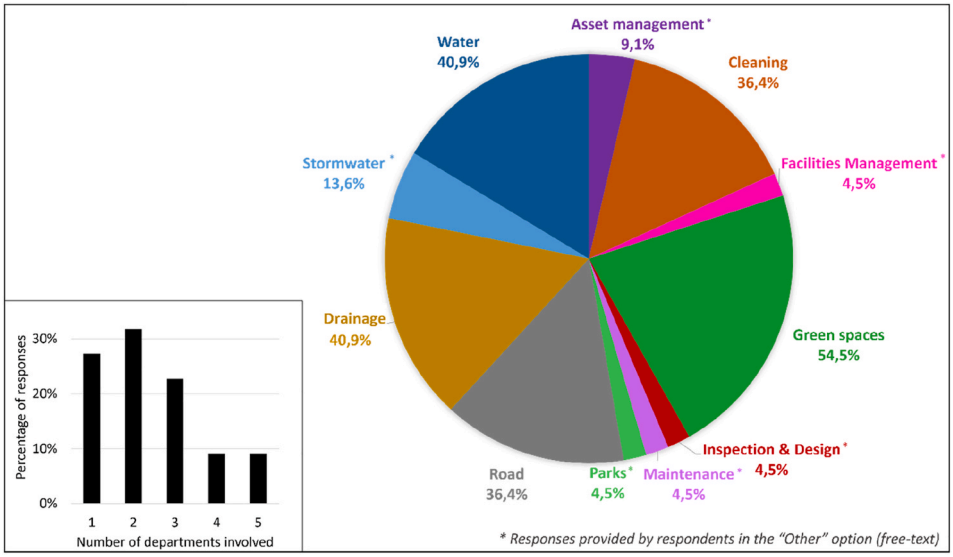



**Fig. 2.** Distribution and number of departments involved in NBSS maintenance according to respondents.

The green spaces department is the most frequently represented, which is expected, given that NBSS are vegetated urban solutions and might therefore be managed similarly to other landscaped areas. Four other core departments of NBSS maintenance also emerge as commonly involved: water, drainage, road, and cleaning services. A dedicated stormwater department is mentioned less frequently, appearing in 14% of responses, as departments exclusively focusing on stormwater can be relatively uncommon. In most cases, stormwater responsibilities are integrated within either water or drainage departments. Notably, 99% of respondents refer to at least one water-related department, which is unsurprising, given the hydraulic functions of NBSS. The involvement of road departments is relevant, as certain NBSS are designed to manage road runoff and may be located along them (e.g., detention basins or roadside swales). Moreover, the cleaning department is also frequently involved as NBSS are urban infrastructures and thus, require routine removal of litter for example.

In the "Other" option, five more departments were cited by respondents. Dedicated asset management departments were identified by 9% of respondents. While relatively recent as an integrated research field, asset management is often examined through its individual components (Girot et al., 2025b) - such as inspection and design as well as maintenance - which were also mentioned as departments involved in NBSS maintenance both by 5% of respondents.

Although a large variety of departments were brought up by respondents, NBSS maintenance is found to spread across a maximum of five different departments for a single organization according to the collected responses. 28% of the respondents mention involving only one department in NBSS maintenance, 32% mention two, 23% mention three, 18% mention four or five. It is important to state that the number of types of departments and the number of departments involved in NBSS maintenance can differ. Certain respondents have mentioned three different department types such as green spaces, road and cleaning involved in NBSS maintenance but state the number two when asked about the number of departments involved. In some cases, a single department might fulfill the roles of multiple department types.

#### 3.2.2. Reporting and legal framework

Moreover, in a context where multiple departments are jointly responsible for NBSS management, we sought to explore documentation and reporting practices in this study, as they underpin knowledge sharing. They also provide a means of determining whether the responses discussed above, particularly regarding the planning of practices, are based on documented data or expert judgment. According to the survey results, observed failures impacting NBSS and the maintenance practices carried out on them are reported and documented by 64% and 55% of the respondents, respectively. Failures are more commonly reported than maintenance practices. These findings suggest that the previous answers are based both on expert knowledge and documented data.

Three types of documentation were reported. The most common and least costly type consisted of written records, including internal logbooks, maintenance guides, OneDrive files, water company reports, and emails. This last option, however, addresses accessibility issues. The second type involved internal Geographic Information Systems (GIS) or GIS-based applications, such as Fulcrum or Brightly Assetic. Finally, some respondents mentioned the use of dedicated internal database software or commercial solutions, such as OptiRTC.

Only 32% of respondents indicated that they use or rely on local or national legal frameworks. The examples provided reveal a wide range of frameworks, from green space regulations, such as the French Labbé Law restricting the use of chemical pesticides on public and private green areas, to urban drainage specifications like the French General Technical Specification Booklets (Fascicules 35 and 70-II) edited by the French Ministry of Public Works. More general frameworks were also cited, such as the Quebec Stormwater Management Guide (Rivard, 2011) as well as maintenance-specific documents like local or regional manuals and guidelines. Among the 32% of respondents who rely on a legal framework, only 14% report their maintenance practices. Among the 68% who do not rely on any legal framework, 41% still document their maintenance activities. These patterns were observed across different NBSS types and countries. These findings indicate that maintenance practices reporting is not necessarily driven by compliance with a legal framework.

### 3.3. Maintenance practices

This section focuses on the collected data regarding maintenance carried out on NBSS. Respondents were asked to select or mention a frequency of practice according to a list of suggested maintenance practices and a specific NBSS of their choice. The distribution of the selected NBSS type regarding most experience in maintenance is similar to that observed for failure, as 64% of the respondents selected the same NBSS type for both sections (Appendix C). This result suggests that for a given NBSS, both failure mechanisms and maintenance practices are known to a similar extent. Understanding the failures of a structure without adequate knowledge of its maintenance practices may prove to be of limited effectiveness.

The practices are divided into two categories that vary in frequency, urgency and impact: (i) routine practices which includes inspection, site maintenance and vegetation management and, (ii) occasional practices which includes targeted cleaning, replacement and performance testing. For each type of practice, the results from the survey and the guideline review are presented sequentially.

#### 3.3.1. Routine maintenance

*3.3.1.1. Inspection practices and site maintenance.* Inspection practices encompass visual assessments of the solution. Site maintenance refers to activities primarily undertaken to enhance the overall condition and appearance of the system, such as litter and debris removal, as defined in Table 1.

***Survey results*** **-** Visual NBSS inspection, by definition the least invasive of maintenance practices, is commonly carried out across most NBSS, with inspection frequencies ranging from monthly to annually, and a notable concentration at the two ends of this range (Fig. 3). However, the inspection frequency varies greatly for a given NBSS type. For instance, in the case of bioretention systems, responses indicated a wide range of practices: one respondent reported monthly inspections, one quarterly, three semiannual, three annual, and one less than annual. No respondents selected "never," suggesting that this practice is systematically considered and has become embedded into established good practices.

Litter and debris removal is a common maintenance practice, most often conducted on a monthly or quarterly basis, as reported by 37% and 27% of respondents, respectively (Fig. 4). However, the frequency of this practice does not appear to be dependent on the type of NBSS. Three respondents reported that the practice was performed as needed, based on visual assessment. Accumulation of litter and debris is primarily driven by external factors in the surrounding urban environment, which are highly context-specific, and maintenance schedules are therefore locally adapted. Litter and debris also represent the most visible form of failure and are relatively straightforward to address. The frequent involvement of cleaning departments in NBSS maintenance, as highlighted previously, likely accounts for the regularity of this practice.

***Guideline review results*** **-** Inspection and site maintenance (e.g., removal of litter, debris, and trash), are also the most frequently cited practice in the guidelines, aligning with the high percentage of response these practices received from survey participants. Regarding frequency, the literature reports a wide range of fixed intervals, from monthly to once every ten years (Fig. 4), with annual inspection being the most commonly reported timing, mentioned in 54% of the guidelines.

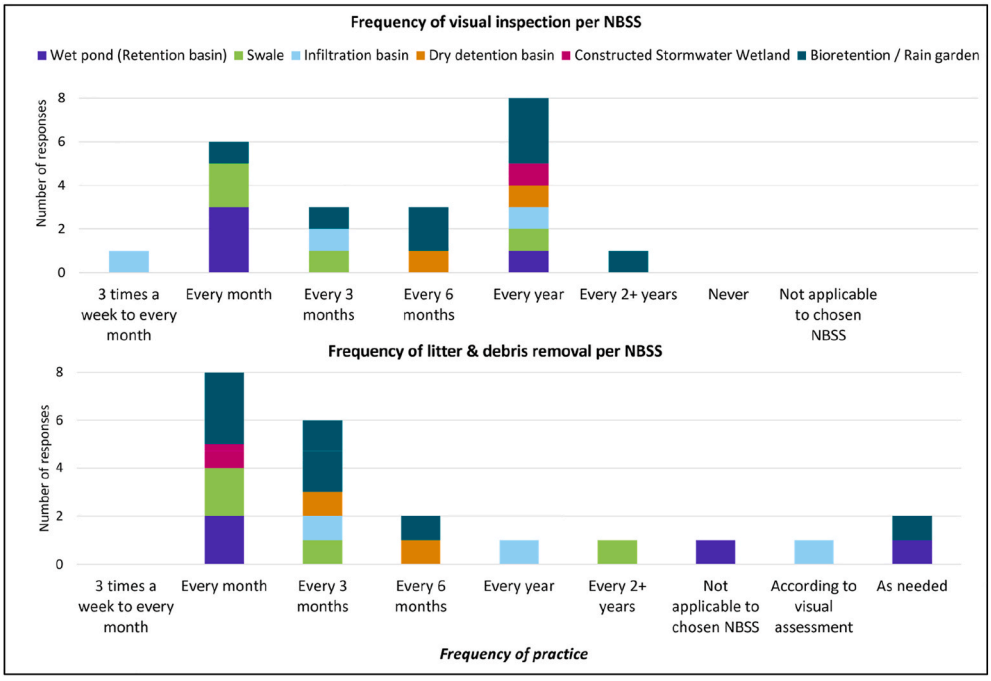



**Fig. 3.** Visual NBSS inspection and site maintenance frequency distribution according to NBSS type (survey results).

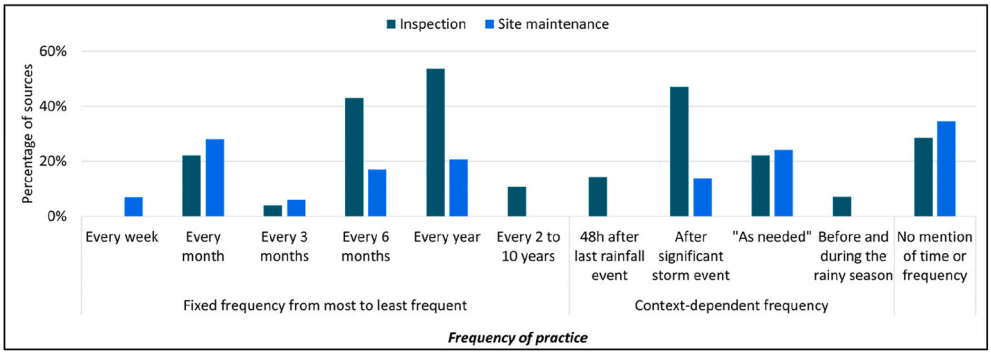



**Fig. 4.** Visual NBSS inspection and site maintenance frequency distribution according to the guideline review of 35 sources.

Flexible, context-dependent timing was also frequently reported, particularly inspection conducted after a significant storm event, which was mentioned in 43% of the guidelines. In addition, 29% of sources did not specify a time or frequency for inspection, likely due to the strong influence of local conditions.

A similarly broad pattern was observed for site maintenance related to litter, debris, and trash removal (Fig. 4). Monthly maintenance was the most frequently reported fixed interval, appearing in 28% of the guidelines, while annual and regular/routine maintenance were each mentioned in 21% of the guidelines. As needed maintenance was also frequently reported, appearing in 24% of the guidelines. Notably, 34% of the guidelines did not specify any time or frequency for this practice, suggesting that maintenance timing is often left flexible and may depend strongly on local site conditions, storm occurrence, and investigated maintenance needs.

*3.3.1.2. Vegetation management and biodiversity-friendly practices.* ***Survey results*** **-** Vegetation-specific inspections appear to be conducted less frequently than visual inspections, with a predominance for quarterly or annual assessments (Appendix E). Conducting inspections on a quarterly basis seems sensible for vegetation, given that seasonal changes significantly affect their performance, and timely intervention could prevent the death of vegetation. Here again, there is considerable variation in the frequency of these inspections for the same NBSS type—for example, swales and bioretention systems. This suggests that vegetation inspection frequency is not primarily determined by NBSS type, but rather by local context and stakeholder expectations. In the sole response concerning constructed stormwater wetlands, vegetation inspections were reported as never being conducted. This may reflect practitioners' confidence in the ecosystem's capacity for self-regulation, resulting in a predominantly passive management strategy (laissez-faire).

Vegetation routine maintenance was presented according to the three main layers identified in an NBSS: herbaceous (ground layer), shrub, and tree. Herbaceous and shrub management was mentioned as most commonly carried out quarterly or annually amongst the represented infiltration systems (i.e., swales, infiltration basins, dry detention basins and bioretention). In the case of wet ponds, the reported inspection frequency ranged from monthly to once every two or more years, which appears rather inconsistent. Regarding tree management, the majority of the respondents selected every two or more years. In some cases, the practice was not applicable to the chosen NBSS (Appendix E).

In this survey, we included a focus on biodiversity-friendly management practices, given that NBSS can host a variety of fauna and flora

when managed appropriately (Pille and Säumel, 2021). The most frequently implemented biodiversity-friendly practices were leaving organic matter on site and promoting the establishment of spontaneous vegetation (Fig. 5). Interestingly, these two practices could potentially contribute to two common failures identified earlier, namely green waste accumulation (causing clogging or suppression of new plant growth) and the spread of invasive plants.

It is worth noting that, most biodiversity-related practices are commonly implemented, suggesting that NBSS co-benefits linked to biodiversity are considered to some extent, albeit not always as a priority. The only practice reported as relatively uncommon is eco-pasture, controlled grazing by livestock, which is understandable given the space requirements that are often unavailable in urban NBSS. Finally, consistent with earlier observations, the implementation of these practices does not appear to depend on the type of NBSS. Rather, it is likely influenced by the type of vegetation, which can vary significantly within the same NBSS type and is largely shaped by local climatic conditions.

***Guideline review results*** **-** The reported practices from the guidelines review are diverse and differ in the level of expertise required. Basic tasks such as leaf blowing, mowing, and weed control coexist with more specialized activities, including pruning, disease management, and replanting (Fig. 6). Overall, the practices most frequently reported across all sources and NBSS types were mowing, followed by replanting, vegetation inspection, watering, and weed control. Pruning and plant cutting were also commonly reported, whereas disease control, plant fertilising, leaf blowing, and ornamental planting were mentioned relatively infrequently. In many cases, either no specific timing or frequency was provided, or practices were indicated to be carried out "as needed", which is in accordance with the survey results. For the practices with recommended fixed intervals, most were suggested to occur at least once per year, although the timing often varies within the season to align with the vegetation cycle (e.g., annual pruning is typically performed in cold season, when most trees are dormant and plant stress and shock are minimized).

In addition, specific instructions were sometimes provided for basic tasks, as certain maintenance activities can be either beneficial or detrimental. For instance, mowing was recommended with the additional step of removing grass clippings from the NBSS. Such specifications can have a significant impact, particularly for assets designed to manage stormwater rather than conventional urban vegetation, as accumulated grass clippings can easily obstruct outlets following rainfall events. Similarly, leaf blowing is not always necessary as leaf litter can provide resources to several soil organisms and contribute to key ecosystem processes (e.g., nutrient cycling), yet they can also clog sewer drains and deteriorate water quality (Perrelet et al., 2024). Identifying thresholds for management activities that benefit urban biodiversity and consider human acceptance of more natural-looking landscapes will help inform effective management practices of these assets (Aronson et al., 2017). Emphasis was also placed on maintenance during the vegetation establishment period, corresponding to the first two years after construction. During this phase, the recommended frequencies of certain practices, such as inspection and watering, were generally twice as high as those recommended after vegetation had become established. Over the long term, studies have shown that spontaneous vegetation and natural water regimes transform the original ecosystem, resulting in a mixture of initially planted and newly colonizing species (Bedell et al., 2021; Pille and Säumel, 2021). This highlights that management interventions when working with nature must vary throughout the lifespan of each NBSS, demanding a flexible and adaptive maintenance strategy. Biodiversity plays a pivotal, often unrecognized, and underexploited role in ensuring that NBSS are effective, resilient, and low-maintenance (Aronson et al., 2017; Perrelet et al., 2024).

*3.3.1.3. Planning.* Lastly, the planning of routine maintenance practices was examined. Respondents were asked to rank triggers for routine maintenance from most to least common. There was a clear consensus that planned maintenance practices occupy the first position. Overall, this indicates that routine maintenance is primarily time-based and scheduled. This finding suggests a shift from run-to-failure approaches (for survey participants), previously triggered by complaints, towards a more proactive maintenance strategy. Visual inspections carried out by operators were predominantly ranked second, while citizen complaints were cited last. This suggests that practitioners generally implement routine maintenance before issues are raised by the public.

### *3.3.2. Occasional practices*

The first category of occasional practices includes targeted cleaning such as sediment buildup removal, and replacement activities involving topsoil or filter media, and vegetation.

*3.3.2.1. Sediment buildup removal.* ***Survey results*** - Sediment buildup removal appears to be planned - or at least carried out at recurring intervals - with reported frequencies ranging from quarterly to annually, by a third of the respondents, regardless of NBSS type (Fig. 7). The predominant reported frequency is once every two or more years, indicating an infrequent intervention, regardless of the accumulation rate. This finding aligns with the results presented in the section on failures, where sediment accumulation was identified as one of the most common issues affecting all three NBSS elements, suggesting that infrequent sediment removal may contribute to sediment-related

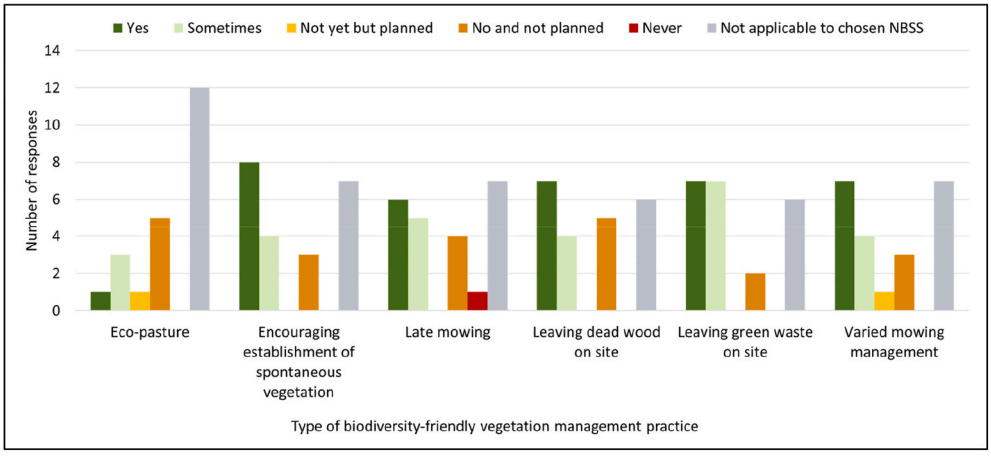



**Fig. 5.** Biodiversity-friendly vegetation maintenance practice adoption level. For each practice (from "eco-pasture" to "varied mowing management"), respondents were asked to indicate its degree of implementation. Implementation levels ranged from fully adopted ("Yes") to not implemented ("No and not planned", "Never").

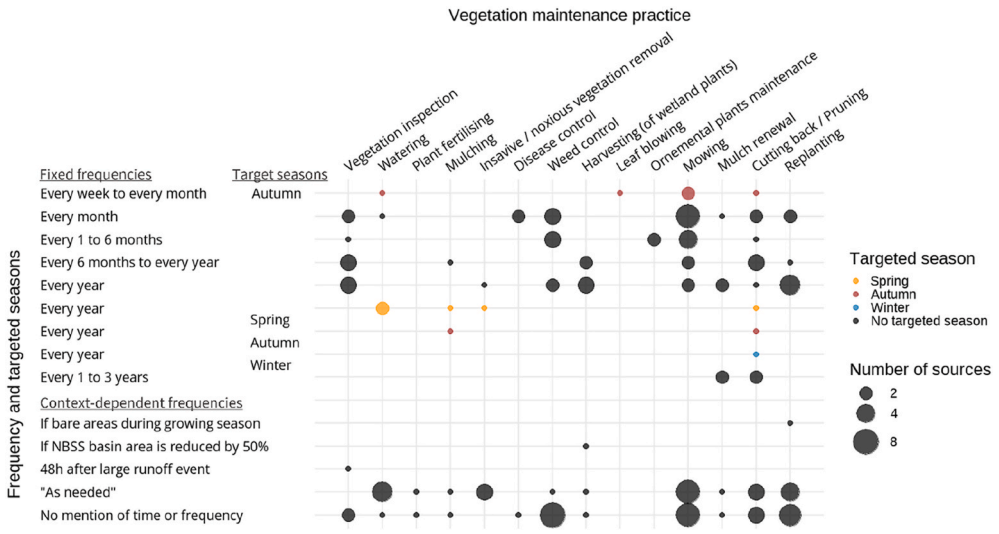



**Fig. 6.** Reported maintenance frequencies and associated target seasons (when specified) for vegetation management practices based on the guideline review.

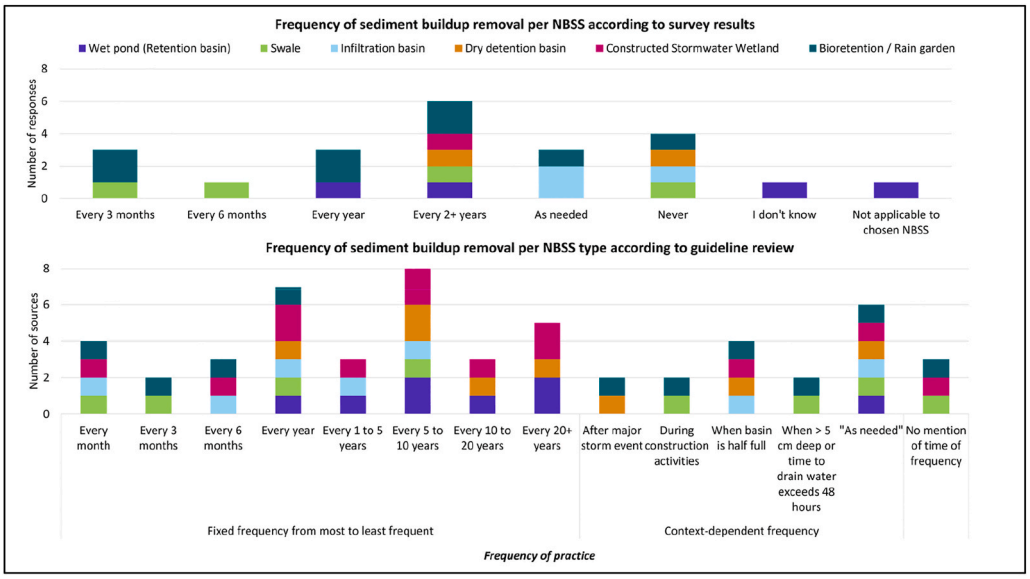



**Fig. 7.** Frequency of sediment removal per NBSS type according to the survey results (top) and the guideline review (bottom).

failures. Some responses refer that sediment removal is not always scheduled and may instead depend on visual inspections; few respondents reported that this practice is never performed. This could also be attributed to the relative youth of some NBSS: the respondents reporting no sediment removal are responsible for systems ranging from less than five years to 20–30 years old. This discrepancy suggests that sediment dynamics remain poorly understood or are highly context-dependent, given the multiple external factors affecting sediment generation and transport into NBSS (Bahrami et al., 2025).

***Guideline review results*** - Across the studied guidelines, sediment removal is also widely reported for most NBSS types. However, the recommended frequency seems to vary depending on the type of NBSS. Larger assets, such as wet and dry ponds as well as constructed stormwater wetlands, generally require less frequent sediment removal, with intervals ranging from annually to once every 50 years. In contrast, smaller assets (e.g., bioretention systems or rain gardens) appear to require sediment removal at least once per year (Fig. 7). In addition to fixed intervals, the literature also suggests context-dependent frequencies. These may depend on seasonal patterns (e.g., "every month during the rainy season"), water storage levels (e.g., "when the basin is half full"), or external anthropogenic factors such as nearby construction activities. "As needed" was also commonly reported across several NBSS types. At the same time, some guidelines did not specify a time or frequency, indicating that sediment removal can be adjusted according to site conditions, sediment build-up, and operational inspections.

*3.3.2.2. Targeted cleaning, repair and renovation.* ***Survey results*** - In terms of topsoil or filter media replacement, the majority of respondents indicated that this practice is never performed for 57% of the respondents (Appendix E). Only five respondents reported performing this replacement at intervals of five years or more and only in the case of bioretention and swales. For the first time in the survey, some respondents also indicated that they do not know, highlighting that these occasional practices are still relatively new and not yet part of a consistent maintenance schedule. Finally, vegetation replacement appears to be carried out annually in some cases (Fig. 8), which can point to several reasons: design flaws (e.g., improper water flow), inappropriate species selection, or maintenance planning choices that favor

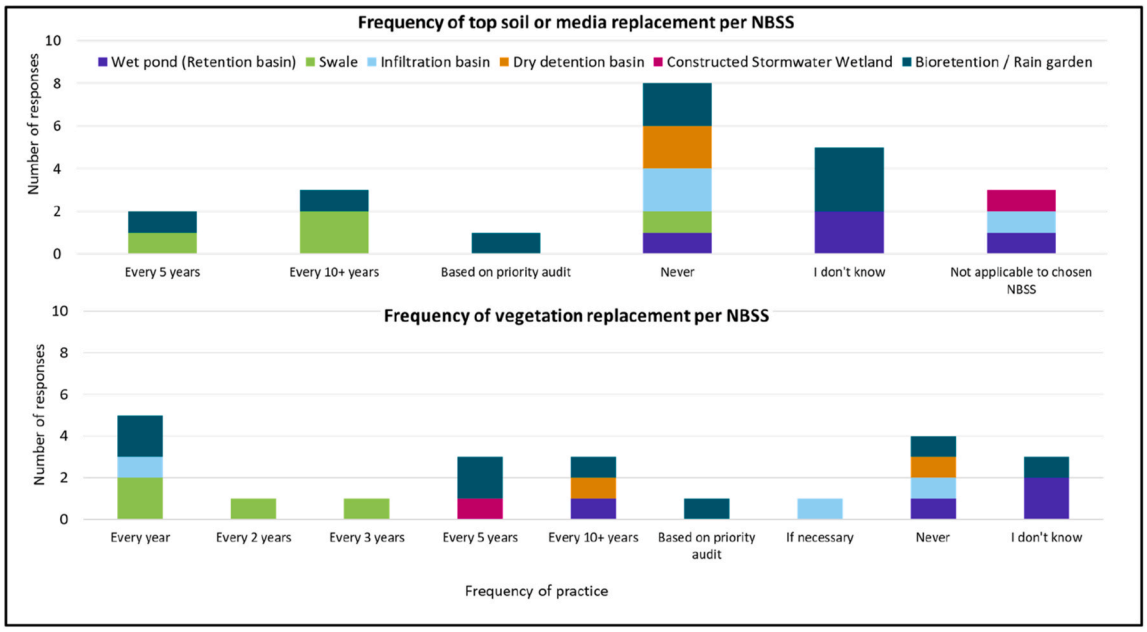



**Fig. 8.** Frequency of top soil or media replacement (top) and vegetation replacement (bottom) per NBSS type according to the survey results.

routine annual replacement over condition-based decisions. Interestingly, earlier results showed that vegetation inspections are conducted fairly frequently. Respondents who reported replacing vegetation every one to three years—mostly managing swales—also cited inspection frequencies ranging from monthly to annually. This indicates that regular monitoring does not necessarily prevent annual vegetation replacement. It is possible that vegetation in swales is particularly sensitive and may deteriorate quickly or unpredictably, particularly in areas with strongly varying seasonal climates (i.e., from cold and wet to hot and dry). On the other hand, some respondents reported replacing vegetation every five years or more, or never. This proves that vegetation dynamics are influenced by a wide range of context-specific factors, including local climatic conditions (e.g., sunlight, rainfall, evapotranspiration) and NBSS characteristics (e.g., soil quality) and urban environmental stressors such as shade or pollution.

*3.3.2.3. Performance testing.* ***Survey results*** **-** The second category of occasional practices encompassed investigation activities, including water quality analysis, soil analysis, and infiltration testing. Across all three practices, a majority of respondents reported that these activities are not conducted (Appendix E). Specifically, 41% of respondents indicated that water quality analysis or infiltration testing is not performed, while 36% reported that soil analysis is not carried out. Some respondents noted that these practices were considered inapplicable to the NBSS type they manage. For example, 22% stated that water quality analysis was not relevant for the NBSS they selected, which included wet ponds, bioretention systems, infiltration basins, and swales. However, water quality analysis should be feasible for these systems, as they manage stormwater and thus have measurable outflows. This suggests that water quality testing is either not regarded as a priority or a core objective of the implemented NBSS, or that it may be considered too costly for routine implementation. Infiltration testing, which is also infrequently performed, could nevertheless provide valuable information to address knowledge gaps regarding the frequency of topsoil or filter media replacement and sediment removal. Despite the high proportion of respondents not performing these practices, a notable number reported conducting them at regular intervals (monthly, yearly, or longer), rather than solely "as needed," indicating that some planning is applied to these advanced practices, likely when they are identified as priorities or when specific infiltration objectives are established for the NBSS. Additionally, a small number of respondents selected "I don't know," reflecting limited familiarity with these techniques, which may be perceived as research-oriented tools that are not easily integrated into routine operational practice. On one occurrence, soil analysis and infiltration testing were reported to be carried out only in cases of confirmed pollution or failure. This suggests that the investigation techniques are used as corrective measures to diagnose and confirm existing issues, rather than as preventive tools to anticipate and avoid potential failures.

## 4. Discussion

### 4.1. Survey strength and weaknesses

In order to reach a broad range of practitioners worldwide while still obtaining a sufficiently detailed overview of management practices, certain compromises were necessary, which may have introduced some ambiguity. A major one concerns the terminology and definition of NBSS. Although the questionnaire included pictures and descriptions of the six NBSS types considered, variations in terminology across regions may have led to confusion. For example, according to feedback from one respondent, swales in North America are sometimes referred to as bioretention systems although they are considered as two different NBSS types in the survey. In addition, respondents were not asked to justify the choice of the NBSS type they selected as the most-well known to them regarding both the failure and maintenance sections. This raises questions as to whether their selection reflected the most commonly implemented system in their area, the one experiencing the most failures, or simply the one perceived as easiest to manage. Furthermore, the relatively low number of responses limits our ability to draw firm conclusions regarding the extent to which the identified practices represent common approaches across NBSS. The participants may have had one of the following reasons to explain this outcome: lack of time, lack of interest, lack of confidence in their responses, limited knowledge, difficulty to gather information due to shared responsibilities or lack of experience due to newly implemented solutions. Although the sample size is very limited, three statistical tests were performed (Appendix F) to identify relationships between NBSS variables and maintenance governance (e.g., NBSS type, age, number of departments involved in maintenance), failure occurrences and maintenance practice

frequencies. No significant result was obtained. Nevertheless, the results provide a valuable qualitative basis for discussion and offer initial practical insights into shared governance, adaptive maintenance strategy, and prevailing practices.

### 4.2. Shared governance

Urban vegetation and urban stormwater which used to be governed separately are now mutually functioning in NBSS (Dhakal and Chevalier, 2016). The hybrid character of NBSS, combining grey and green components, requires a broad range of expertise for effective management. Multiple disciplines, sectors, and operational scales are therefore involved, as reflected in the representation of 11 different departments in the survey. This multidisciplinary configuration creates governance challenges, as coordination and communication across fields - from ecological science to water management - are hindered by institutional fragmentation and no clear definition of leadership in existing professional jurisdictions. Dhakal and Chevalier (2016), in their study of stormwater governance in five leading U.S. cities implementing NBSS, found that while centralized stormwater agencies typically took the lead, other functions with significant influence on stormwater management (e.g., park maintenance) fell under separate jurisdictions. Such organizational fragmentation has been widely identified as a major barrier to NBSS implementation (Qiao et al., 2019; Thomas, 2020), and more recently, to their long-term management and maintenance (Knapik et al., 2025). Maintenance, in particular, is frequently overlooked in NBSS asset management due to insufficient funding and limited institutional incentives (Harvey et al., 2009). Many financial mechanisms rely on one-off capital investments without accounting for long-term operational and maintenance requirements (Knapik et al., 2025). In fact, in the final question left open for additional comments, one respondent stated:

> "There's a lot of pressure to create these, but many policy-making bodies conveniently forget that they also need to be maintained and that this costs money."

Although maintenance of NBSS typically involves multiple departments, there is no standardized or unified approach to organizing these responsibilities. In some contexts, asset maintenance is consolidated within a single department for the sake of simplification. In such cases, that department may be required to undertake tasks beyond its traditional expertise - for instance, drainage maintenance teams removing litter from retention basins. Alternatively, several departments responsible for different functions of the asset may operate within the same space. While each department then performs its conventional duties, this arrangement challenges the inherited socio-spatial division of labor rooted in silo-based municipal organizations, thereby necessitating coordination (Cossais, 2021). To address these governance challenges, numerous frameworks promoting cross-sectoral collaboration have been developed (Hohmann et al., 2025; Naumann et al., 2023). However, there is no single optimal governance model for NBSS maintenance. Instead, the inherently diverse and context-specific character of NBSS calls for flexible governance arrangements (Damman et al., 2025).

While no single unified governance model exists, the role of leadership emerges as a critical factor in the success of NBSS, raising the question of how such systems can function effectively in the absence of clearly defined leadership within municipalities (Hohmann et al., 2025). Clear allocation of leadership and responsibility has been identified as a key governance condition (Qiao et al., 2019), a point echoed by one respondent in the final open-ended question, who noted:

> "Leadership to resolve maintenance funding and proactive asset management is critical to the delivery of consistent and high-quality maintenance outcomes."

In some contexts, formal guidelines specify departmental responsibility according to the characteristics of the NBSS. For example, in Lyon, France, management of a swale falls under the water department if it hosts no trees, but shifts to the parks and gardens department if at least one tree is present. Beyond such rule-based allocations, alternative organizational arrangements could be considered. One possibility would be restructuring departmental responsibilities so that representatives from multiple departments collaboratively manage shared geographic areas, rather than each department overseeing the entire territory independently. Given that NBSS are dynamic systems shaped by intertwined socio-ecological-technological interactions, governance structures require flexibility and integrative leadership to ensure adaptability and long-term sustainability (Damman et al., 2025).

Understanding the complex interactions within this system depends on multi-disciplinary maintenance teams that share expertise and knowledge. Practically, it also relies heavily on routine inspections, which help build insights into the context-specific evolution of the NBSS as well as reporting, which is still not commonly implemented as seen by the survey results. 45% of the respondents reported not documenting the maintenance practices carried out. Similar findings were reported by Sañudo-Fontaneda et al. (2026) in a study investigating practitioners' monitoring practices, where only 39.5% of respondents indicated that they monitored their practices, and merely 14.6% reported systematically monitoring their implemented NBSS. The accessibility, long-term preservation, and accuracy of this knowledge for supporting decision-making require the implementation of a structured reporting tool. Such a tool would facilitate the sharing of information regarding who performs specific tasks, when they are carried out, and for what purpose, provided that it is hosted on a collaborative platform. As noted earlier, some respondents currently rely on written documents such as emails, internal logbooks, and files, which are not always well suited to open access and collaborative work. A joint tool would also provide a platform for discussing maintenance priorities and role distribution. One respondent also stressed the difficulty of implementing the use of such a reporting tool in the final open-ended question:

> "Software that includes maintenance checklists, schedules, and attendance records is only valuable if staff are supported in using it."

Support can take various forms. It might involve financial investment in software development and allocating human resources so that maintenance teams have the time and capacity to carry out maintenance checklists. It can also include workshops and training aimed at helping staff use the tool effectively. In addition to documenting maintenance activities, these tools could support the systematic reporting of system failures. Although several studies have investigated NBSS failure mechanisms, these analyses remain largely qualitative due to the limited availability of failure data for quantitative assessment (Bahrami et al., 2024; Almasalmeh et al., 2026) and are therefore very rarely included in long-term modeling of these systems which hinders associated results (Wu et al., 2024). Systematic reporting and quantification of failure occurrences would significantly support the development of long-term performance models and adaptation of maintenance plans.

However, such tools or softwares supporting data documentation, structuring, and management must account for the inherent complexity of the socio-institutional systems involved in NBSS asset management. They should allow knowledge sharing between multiple departments, often with varying priorities and levels of expertise (Cossais, 2021). They must also remain sufficiently adaptable to be tailored to each asset's environmental context, including local hydrology, climate conditions, and ecosystem characteristics. This includes factors such as the catchment's urban density, the NBSS's main hydrological role (i.e., infiltration, retention, or sedimentation), the local climate ranging from arid to tropical, and lastly the vegetation, which can be spontaneous or planted, perennial or seasonal, and may vary in species across different strata. This diversity accounts for the complexity of studying these systems and the management strategies they require, but is also the key to the multiple benefits associated with NBSS (e.g., urban cooling effect,

air pollution reduction, biodiversity enhancement).

### 4.3. Adaptive maintenance strategy

Despite the diversity of NBSS types represented in the survey, respondents reported similar types of failures and maintenance practices. Moreover, the frequency at which maintenance activities are performed does not appear to vary according to NBSS type. We sought to examine whether maintenance frequency might be associated with NBSS age, the number of employees or departments involved in maintenance. However, the limited sample size (n = 22), distributed across four age categories and three organization size categories, substantially reduces the statistical power of the analysis, and therefore limits the results' interpretation. The Spearman's rank correlation analysis did not yield conclusive results (Appendix F). This limitation is further reflected in the visual interpretation of the graphs showing maintenance practice frequencies according to NBSS age and the number of employees or departments involved in maintenance (Appendix F), which reveals considerable variability in the observed patterns. This raises the question of whether strict standardization of maintenance frequency should even be the objective. According to Knapik et al. (2025), "most of the literature points out the relevance of context-specific maintenance for NBS successful performance". Managing natural elements is not easily replicable from one NBSS to another or from one climate to another. Effective maintenance should be grounded in a thorough understanding of the specific ecological and hydrologic dynamics of each solution. This divergence is also reflected in grey literature where frequency of practice shows similar results as the survey's.

Moreover, budget allocations for investigative practices are likely limited and therefore may not constitute a primary concern for practitioners (Sañudo-Fontaneda et al., 2026). However, such practices provide essential information to assess whether NBSS function as intended and whether they achieve their designed impact and efficiency. In contrast to water quality or soil analyses - which were reported as rarely performed in the survey - infiltration tests require comparatively fewer resources in terms of time, expertise, and equipment. If conducted more regularly, they could provide valuable quantitative information to complement visual assessments of system performance and maintenance needs, such as top soil or filter media replacement. In practice, infiltration testing is often carried out at the beginning of a system's life cycle to verify that the constructed NBSS meets design specifications, as mentioned by a respondent from the survey. However, this initial test is generally considered a commissioning step rather than a maintenance activity, as it is typically performed only once at the start of system operation. Similarly, soil analysis was reported to be performed only in cases of confirmed pollution (Appendix E), which limits the effectiveness of this technique as a tool for preventive maintenance. Monitoring throughout long-term maintenance, whether it is for infiltration rates, soil quality or vegetation species composition, is essential to ensure NBSS performance, adaptability, and the effective implementation of adaptive NBSS management (Rey et al., 2026). Low-cost technologies for monitoring are on the rise and opening new potentials for long-term data acquisition (Cherqui et al., 2019). Achieving this, however, requires improved knowledge transfer, particularly from research to practice.

Beyond its multidisciplinary nature, maintenance should therefore also be transversal, bridging the gap between research and operational practice. The current global increase of NBSS implementation represents a critical opportunity for researchers to leverage the living laboratory formed by the growing number of NBSS scattered across the urban landscape. Systematic data collection and long-term archiving over the coming decades will be essential. Several frameworks already exist to assess the sustainability and multifunctionality of NBSS projects (Helness and Sivertsen, 2025; Sowińska-Świerkosz and García, 2021; Wang et al., 2019; Sørup et al., 2019). However, without robust datasets—and particularly long-term monitoring data—drawing meaningful conclusions about the actual multifunctionality and effectiveness of these systems remains premature. Monitoring and inspection strategies must therefore be carefully designed, specifying what data should be collected, how it should be collected, and at what temporal frequency (Lynn et al., 2026). This also presents an opportunity for closer collaboration with practitioners, who have direct operational experience with NBSS implemented on their territory, as well as early coordination and involvement of stakeholders.

## 5. Conclusion

This survey provides valuable practitioner feedback on NBSS failures and maintenance practices across several countries. In light of the limited number of responses and geographic coverage, despite the effort to question practitioners in their own language, only a few NBSS managers are willing and able to provide a comprehensive view of failures and maintenance practices implemented. This limits the ability to determine whether the observed similarities reflect widespread maintenance practices or are influenced by sampling variability. However, this observation is consistent with the current state of the scientific and grey literature on the subject. Nevertheless, the survey offers a qualitative overview of common failures and insights into current practices, disregarding NBSS type.

Inlets, pretreatment devices, outlets and overflow devices seem to be mainly impacted by sediment, trash and green waste accumulation as well as overly dense vegetation. The latter is also is also a major contributing factor to failures in the main ponding area, along with the spread of invasive plants. These findings highlight the central role of vegetation in ensuring the proper functioning of NBSS. Consequently, such failure mechanisms should be examined in greater detail to better understand NBSS dynamics over time and included in long-term models. In terms of maintenance, common practices generally aim to address or prevent the corresponding failures. Visual site inspections appear to form the foundation of maintenance strategies, with frequencies ranging from monthly to annually. Site maintenance including litter and debris removal is carried out more frequently, on a monthly to quarterly basis. Vegetation-related practices tend to follow seasonal cycles, with inspections and management of herbaceous plants and shrubs usually conducted every three months to once a year. Finally, sediment removal follows a slower dynamic and is therefore generally performed annually or less frequently.

Notably, practitioners' operational maintenance feedback aligns broadly with findings from the literature. Grey literature, particularly drawn from O&M guidelines, similarly both refer to these common practices and reflect a diversity of frequency recommendations. Even among a small set of guidelines from the United States, Canada, Australia, and France, no single maintenance strategy prevails, likely reflecting the context-specific nature of NBSS in urban environments. Maintenance frequencies cannot be defined in absolute terms, as they depend on factors such as vegetation and local urban conditions. In retrospect, there was a clear need to incorporate more context-related questions into the survey to better interpret the results. However, doing so would have made the survey more time-consuming and complex to complete, resulting potentially in an even lower number of responses. A more effective approach may be to use a simpler, more focused survey to identify knowledgeable experts, followed by in-depth interviews.

## CRediT authorship contribution statement

**Emma Girot:** Writing – original draft. **Ning Ding:** Writing – original draft. **Ivar Annus:** Writing – review & editing. **Elena Cristiano:** Writing – review & editing. **Sophie Duchesne:** Writing – review & editing. **Tim Fletcher:** Writing – original draft. **Perrine Hamel:** Writing – review & editing. **Florian Kretschmer:** Writing – review & editing. **Jeroen Langeveld:** Writing – review & editing. **Marius Møller Rokstad:**

Writing – review & editing. **Franz Tscheikner-Gratl:** Writing – review & editing. **Corinne Curt:** Writing – review & editing. **Franck Taillandier:** Writing – review & editing. **Frédéric Cherqui:** Writing – review & editing.

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this article, the authors used ChatGPT solely to assist with language editing, wording, concision, text structure, and readability, based on text originally written by the authors. The tool was not used to generate research ideas, produce or analyse results, interpret data, draw conclusions, create figures or tables, conduct the literature review, or add scientific content or references. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

## 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.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.131319.

## Data availability

Data will be made available on request.

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