Asset management for blue-green infrastructures: a scoping review

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Blue-Green Systems

 Blue-Green Systems Vol 4 No 2, 272 doi: 10.2166/bgs.2022.019

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Jeroen G. Langeveld [a,*], Frédéric Cherqui [b], Franz Tscheikner-Gratl [c], Tone Merete Muthanna [c], Marina Fernandez-Delgado Juarez [c], Joao P. Leitão [d], Bardia Roghani [c], Karsten Kerres [e], Maria do Céu Almeida [f], Caty Werey [g] and Bénédicte Rulleau [h]

[a] Faculty of Civil Engineering and Geoscience, Department of Water Management, Delft University of Technology, Delft, The Netherlands
[b] Univ. Lyon, INSA Lyon, DEEP EA 7429, F-69621 Villeurbanne cedex, France
[c] Department of Civil and Environmental Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[d] Department of Urban Water Management, Eawag, 8600 Dübendorf, Switzerland
[e] Faculty of Civil Engineering, Aachen University of Applied Sciences – FH Aachen, Aachen, Germany
[f] Department of Hydraulics and Environment, LNEC, 1700-066 Lisbon, Portugal
[g] INRAE, UMR GESTE, Engees, Strasbourg, France
[h] INRAE – ETTIS, 50 avenue de Verdun, 33 612 Cestas, France
*Corresponding author. E-mail: j.g.langeveld@tudelft.nl

JGL, 0000-0002-0170-6721; BR, 0000-0001-5435-6748

ABSTRACT

Urban drainage systems have developed way beyond the traditional piped combined or separate sewer systems. Many 'new' systems are being introduced, ranging from stormwater infiltration facilities to green roofs. However, the widely advocated blue-green infrastructures are typically overlooked by asset managers, which will very likely have detrimental effects on their performance, service life, and wider adoption. In this paper, the working group on Urban Drainage Asset Management (UDAM – https://udam.home.blog/) of the IWA and IAHR Joint Committee on Urban Drainage discusses whether the state-of-the-art knowledge based on conventional sewer asset management is sufficient to develop asset management for blue-green infrastructures (BGIs). The discussion is structured around the five preconditions for effective control and asset management. Results show that asset management for BGIs is still underdeveloped due to a lack of monitoring techniques covering the broad range of BGI benefits and performance indicators, inspection techniques covering relevant failure mechanisms and models describing these mechanisms, maintenance and rehabilitation options, and sufficient support tools to aid inhabitants in the operation and maintenance of their individual BGIs such as green roofs or vegetated swales.

Key words: nature-based solution, stormwater control measures, urban drainage

HIGHLIGHTS

- Blue-green infrastructures (BGIs) are widely applied.
- The asset management of BGI is lacking behind.
- Monitoring and inspection techniques for BGIs are underdeveloped.
- Rehabilitation techniques for BGIs are too limited.
- BGI deterioration models need development.

INTRODUCTION

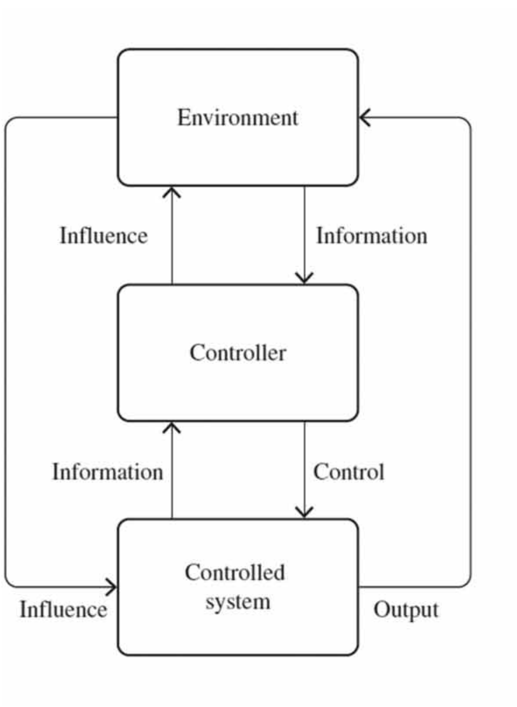
The evolution in stormwater management in the last decades has been substantial. Drivers of this evolution include current challenges such as budget limitations, urbanization, environmental protection, stricter regulations as well as the 'near' future challenges associated with climate change adaptation and mitigation. Evolution is fostering the adoption of blue-green or hybrid 'grey-green' infrastructures, in the replacement of or in addition to piped networks, often designated as 'grey' infrastructures.

The blue-green infrastructures (BGIs) bear different names often related to their objectives, among others low impact development (LID), water-sensitive urban design (WSUD), and sustainable drainage systems (SUDS) (see Fletcher *et al.* (2015) for a more complete list). More recently, these infrastructures are seen as key elements of the so-called sponge cities in China (Jiang *et al.* 2018) and are also called nature-based solutions (NBS) elsewhere. According to Raymond *et al.* (2017), NBS are 'solutions to societal challenges that are inspired and supported by nature'. In other words, they 'address societal challenges (e.g. climate change, food, and water security, pollution control, or natural disasters) effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits' (Cohen-Shacham *et al.* 2016).

Currently, rapid uptake of BGIs, such as bioswales, green roofs, permeable pavements, and retention spaces in parks (Tillie & van der Heijden 2015), can be found in many countries as a response to climate change and water quality issues. Within the EU, the Proposal for a revised Urban Wastewater Treatment Directive (EU 2022) advocates BGIs as a means to reduce surface water quality issues. The current focus is the design, placement, construction, and further development of BGIs. However, BGIs need to be operated, maintained, and rehabilitated to ensure expected performance. For grey infrastructures, such as sewer systems, asset management is widely applied to ensure the needs of operation, maintenance, and rehabilitation based on decades of experience in practice and research (in that order!), resulting in widely accepted inspection and rehabilitation techniques. Whereas decades of development have resulted in common ground for sewer asset management in terms of the use of CCTV inspection, deterioration modelling, codes and regulations, and decision-making, despite several shortcomings and deficiencies in knowledge (Tscheikner-Gratl *et al.* 2019), for BGIs, the situation is less obvious. These infrastructures show a wide diversity in terms of their type (ranging from bioswales, green roofs to urban ponds), spatial scales (ranging from individual facilities on plot level, swales serving entire neighbourhoods to wetlands serving sub-catchments), level of multi-functionality, and actors involved in operation and maintenance (O&M). Consequently, their asset management is potentially more challenging than grey infrastructures.

In this review paper, we assess whether the concept of sewer asset management can be applied to BGIs. The concept of asset management is analysed by evaluating the potential to successfully apply the well-known Deming cycle (Plan–Do–Check–Act) (Moen 2009). This learning cycle can only successfully be applied if five general preconditions for effective control are met, see Figure 1 (De Leeuw 1974; van Riel *et al.* 2014).

The first section of the paper shortly describes the concept of sewer asset management and the differences between sewer asset management and asset management of BGIs. We also present in this section the results of a quantitative literature survey on asset management for BGI. The consecutive sections systematically assess whether the current state of the art is sufficient to fulfil the five conditions for effective control. The paper concludes with an overview of research needs.



Condition 1. The controller has an objective and an evaluation mechanism to check whether the goals are met.

Condition 2. The controller has a model of the controlled system to predict the effect of potential control actions.

Condition 3. The controller has information about the environment and the controlled system.

Condition 4. The controller has sufficient control actions to cope with the variability of the system.

Condition 5. The controller has sufficient information processing capacity to transform incoming information into effective control actions in line with the objectives.

Figure 1 | Control paradigm of De Leeuw (1974), reproduced with permission from Van Riel *et al.* (2014).

SEWER ASSET MANAGEMENT VS. ASSET MANAGEMENT OF BLUE-GREEN INFRASTRUCTURES

Asset management can be defined as the coordinated activities of an organization to realize the value of assets (ISO 55000). More precisely, asset management refers to a systematic approach to the governance and realization of value from the things that a group or entity is responsible for, over their whole life cycles. It is the systematic process of developing, operating, maintaining, upgrading, and disposing of assets in the most cost-effective manner (including all costs, risks, and performance attributes). Or, as Brown & Humphrey (2005) put it: 'Asset management is the art of balancing performance, cost, and risk.' It can apply both to tangible assets (physical objects such as buildings or equipment) and intangible assets (such as human capital, intellectual property, goodwill, or financial assets).

Infrastructure asset management became a very important issue in most developed countries in the 21st century since the majority of their infrastructure networks were constructed during the 20th century, and they have to manage, operate, and maintain those ageing systems cost-effectively (Vanier 2001).

Traditional sewer system (grey infrastructure)

The traditional European and North American sewer system was initiated in the late 19th and early 20th centuries. Numerous components from the founding period are still in operation. The main expansion phases were executed from 1960 to 1980. The public sewer system is characterized by standardized and technically comparable system elements (e.g. pipes, connections, manholes, inlets, and gully pots). In addition, there are comparatively few outflow elements, such as combined sewer overflows or pumping stations.

Both defect detection and condition assessment are widely standardized. Thus, there are established methods to determine minimum performance levels as specified in the European standard EN 752. Also, whole life cost approaches to managing the assets are applied. Finally, there are solutions to elaborate appropriate asset management plans for conventional sewer systems or 'grey infrastructure' (see Alegre & do Céu Almeida 2009).

Furthermore, owners or operators of the sewer systems are often public authorities or commissioned third parties. Ownership, responsibilities, and tasks are regulated in many countries and, as expected, there are both resources and competencies to operate asset management according to the IAM (www.theIAM.org) or ISO 55000 approaches.

Blue-green infrastructures

BGIs provide the 'ingredients' to solve urban and climatic challenges by 'building with nature' (Pötz & Bleuze 2011). These comprise stormwater management, climate adaptation, less heat stress, more biodiversity, food production, better air quality, sustainable energy production, clean water and healthy soils, as well as the more anthropocentric functions such as increased quality of life through recreation and providing shade and shelter in and around towns and cities. BGI can be considered a subset of 'Sustainable and Resilient Infrastructure', which is defined in standards such as SuRe (sure-standard.org). BGI can also be a component of 'sustainable drainage systems' or 'sustainable urban drainage systems' (SuDS or SUDS), LID, or WSUD, which are designed to manage water quantity and quality while supporting biodiversity and providing amenities. In this case, BGI tends to be named Stormwater Control Measure (SCM) (Fletcher *et al.* 2015).

BGI has developed as an idea over the last 20–40 years, driven by the need to respond to climate change impacts resulting in more urban flooding and drought issues. The components of BGI, as well as the ownership responsibilities, are often not well-structured and are characterized by low automation, proximity to nature, small spatial scale, and individuality (Cherqui *et al.* 2019a, 2019b). Accordingly, competencies and resources for asset management are often not available in the classical sense. This makes BGI significantly different from grey infrastructure, technically, structurally, as well as organizationally.

To date, most of the present management of BGIs is based on the run-to-failure approach, partly due to resource limitations and lack of knowledge. It is, for example, not possible today to accurately predict the evolution of hydraulic parameters such as filter media permeability (Gonzalez-Merchan *et al.* 2012). Limited resources do not allow for frequent or continuous monitoring of each BGI and utilities often choose to monitor the most important BGIs in size or regarding the consequence of a failure (Cherqui *et al.* 2019a, 2019b). BGI asset management strategies must rely on the knowledge, experience, and practices developed for 'traditional' infrastructures. Such materials will, however, need to be adapted to BGIs to consider the specificities of nature-based solutions such as BGIs, as presented in Table 1.

Table 1 | Comparison between 'traditional' water infrastructure (i.e. water or wastewater pipelines) and BGI (Cherqui *et al.* 2019a, 2019b)

'Traditional' water infrastructures	BGI
Continuous system: the network is composed of pipes linked together	*Discontinuous system*: BGIs are often spread individually on the territory aiming to manage stormwater 'at source'
Single purpose: pipes are designed to convey water from one point to another	*Multi-functionality*: in addition to runoff management, BGIs can improve biodiversity and provide social benefits, etc.
Assets are 'grey' (man-made) and depend on the civil engineering field	*Assets are 'grey' and 'green'* (nature-based) and depend on the civil engineering and the ecosystem fields
Immediate effect of rehabilitation: the asset is back to normal functioning after the construction works	*Nature time-scale dependent*: any rehabilitation involving a nature-based component can need time to fulfil completely its function
All assets are very similar and are often considered homogeneous groups (cohorts)	*Each asset is unique in* terms of size, form, and constitution and service delivered, and thus requires a unique model
Assets are hidden underground: they are not visible but can be distinguished from other urban elements	*Assets are integrated* within an urban environment, and it can be a road, a playground, a sports field, a park, etc.
Assets are managed by one department which can be the water department or sanitation department	*Assets require collaborative management* between, for example, water department, street cleaning department, and green space service

BGIs, such as infiltration trenches and swales, have seen a rapid uptake since the end of last century, at first predominantly as a measure to reduce combined sewer overflow (CSO) emissions. Since their emergence, operational and research questions have largely focused on optimizing hydrologic, hydraulic, and water quality performance. After several decades of operation, there is, however, a growing concern regarding their medium- and long-term performance and maintenance. This growing concern is confirmed by recent studies such as Allison & Francey (2005), Duffy *et al.* (2008), Shirke & Shuler (2009), Bastien *et al.* (2010), Drake & Bradford (2013), Al-Rubaei (2016), Cossais *et al.* (2017), Werey *et al.* (2017), and Cherqui *et al.* (2019a, 2019b). These infrastructures remain a poorly understood but a relatively important asset in cities: for instance, Lyon Metropolis (France) recently commenced such an inventory and identified 200 + infrastructures to date in public areas, while Bordeaux (France) and Melbourne (Australia) are expecting even 10,000+ (Bourgogne 2010; Milenkovic *et al.* 2012). The question of their maintenance is becoming a major disincentive for the adoption of BGIs. Local governments are at risk of withdrawing from BGI implementation, driven by concerns about the long-term financial and operational sustainability of such systems (Morison *et al.* 2010; Erickson *et al.* 2018).

Quantitative literature review

While asset management of urban water infrastructures, such as drinking water or wastewater pipelines, has been deeply investigated, research on BGIs asset management remains a new field (Al-Rubaei 2016; Cossais *et al.* 2017; Werey *et al.* 2017). This can be inferred from the results of the quantitative literature review presented in Table 2. The quantitative review was conducted based on combinations of the term 'Asset Management' with the various terms for 'Blue-Green Infrastructure' (LID, SUDS, WSUD, SCM, and NBS). It is important to highlight that for more generic searches, as for the terms 'Asset', 'Management', 'Blue', 'Green', and 'Infrastructure' are considered, the publications' search produces significantly larger numbers of results, but most of them are not related to urban drainage systems.

The number of scientific publications about 'Blue-Green Infrastructure' (102) is significantly larger than those related to 'Sewer Asset Management' (37), despite the earlier year of publication (2003) of the first publication of 'Sewer Asset management' papers compared to the year of the first publication on 'Blue-Green Infrastructure'.

The number of publications explicitly dedicated to the management and maintenance of 'Blue-Green Infrastructure' is still very small. Only three scientific publications addressing this topic have been published so far:

- Angle (2010) was one of the first to identify the need to monitor and maintain BGI in the long term (in his study he uses the term LID) and highlights the important role of asset management in the overall stormwater management programmes.

Table 2 | Quantitative results of the literature search

Search keywords (and most relevant publications)	No. of publications	Date of first publication
'Sewer Asset Management' (e.g. Le Gauffre *et al.* 2007; Ana *et al.* 2009)	40	2003
'Blue-Green Infrastructure' (e.g. Barthel & Isendahl 2013; O'donnell *et al.* 2017; Thorne *et al.* 2018)	137	2010
'Blue-Green Infrastructure' (and) *'Asset Management'*	0	–
'BGI' (and) *'Asset Management'*	0	–
'NBS' (and) *'Asset Management'*	0	–
'LID' (and) *'Asset Management'* (e.g. Angle 2010; Blecken *et al.* 2017; Mullaly 2019)	4	2010
'WSUD' (and) *'Asset Management'* (Blecken *et al.* 2017)	1	2017
'SUDS' (and) 'Asset Management'	0	–
'Stormwater control Measures' (and) *'Asset Management'* (e.g. Blecken *et al.* 2017; Mullaly 2019)	13	2017

The references included in the table are those among the results that are directly related to the topic of BGI asset management (information retrieved from Scopus on 23 September 2021).

- Blecken *et al.* (2017) showed the various negative impacts resulting from the lack of maintenance of BGI that can lead to the failure or limited functional performance of these infrastructures. In their study, they have highlighted possible reasons for the lack of maintenance of these urban drainage infrastructures: '… insufficient communication, unclear responsibilities, lack of knowledge, financial barriers, and decentralised measures.'
- The most recent publication dedicated to the 'asset management' practice of BGIs is the book chapter presented by Mullaly (2019). In this chapter, it is highlighted that the different BGIs need to be appropriately managed to ensure they provide the function they were designed for. Also, the author identified deficiencies in the management of this type of urban drainage asset, but some improvements could already be reported in recent years. This is again a clear indication that there is an urgent need to look at BGI asset management practices around the world.

The three publications found in the literature search and, briefly described above, clearly highlight the need for the development of dedicated BGI asset management methods. In addition to the reasons identified by Cossais *et al.* (2017) such as the lack of consideration of long-term O&M implications in the planning stage and demarcation of responsibilities, other reasons can also explain the limited research on this topic: the relatively recent development of the BGI for urban drainage purposes, the relatively small number of applications, limited O&M data of this type of infrastructure, and the individual ownership nature of these systems or assets.

A few other papers may exist on the topic of BGI and asset management that were not identified during the structured literature search in Scopus (September 2021). Examples of such works can be abstracts included in conference proceedings (e.g. Cherqui *et al.* 2019a, 2019b) and Master and Doctoral theses (e.g. Martínez 2016).

CONDITIONS FOR EFFECTIVE CONTROL

Given the large diversity in BGIs, we have used the control paradigm of De Leeuw (1974) as a conceptual and general framework to determine that asset management can be applied to any type of urban drainage system. The control paradigm has been applied previously to sewer asset management by Van Riel *et al.* (2014). The control paradigm of De Leeuw uses the model shown in Figure 1. The system (a sewer or a BGI) is controlled by the controller (asset operator, asset owner, etc.) using the information on the condition and performance of the controlled system. The controller also uses information from the environment (such as the impact of CSO spills on receiving water quality or road potholes due to pipeline structural collapse for sewers, contribution to urban heat island effect, or biodiversity of green roofs) by defining the control actions. Finally, the environment affects the performance of the controlled system (e.g. infiltration capacity of a grassed swale can be affected by the use of the swale as a playground) and the performance of the controlled system affects the environment (e.g. failure of swale functions can hamper the use of the facility as a playground).

Condition 1. The controller has an objective and an evaluation mechanism to check whether the goals are met

The main function of a piped drainage network is to convey waste- or/and stormwater away from the urban area; this is often more complicated with BGI. BGIs are typically integrated within the urban landscape, most often open-air, and thus have high visibility and public accessibility. Being open-air, the allocated space cannot be dedicated solely to stormwater management. As it is not raining most of the time, the infrastructure will often have a main function not related to water management: such as parking, driving, riding, walking, or recreation, as illustrated in Figure 2.

When considering the whole urban drainage system, it is expected to fulfil several functions related to the city or the environment. Concerning the development of BGIs, such expectations have emerged from the concept often referred to as sustainable urban water management – SUWM (Larsen & Gujer 1997; Hellström *et al.* 2000; Brown *et al.* 2006). Expectations related to SUWM can differ from place to place according to the local context and their typologies. However, there is a strong need for an exhaustive list of services that sustainable urban water management can provide. This exhaustive list is required to guide the utility manager in the identification of the services specifically for the territory. Belmeziti *et al.* (2015) have translated this concept in terms of functions that the system must fulfil, including hydraulic and pollution reduction functions next to the preservation of the natural environment, protection of human health, and guaranteeing social equality. However, there is still an important gap between these functions and the means (indicators) to assess them, either because of lack of knowledge or because of lack of monitoring methods and capabilities (Belmeziti *et al.* 2015).

So far, most efforts have been dedicated to the assessment of performance related to water quantity and quality. Quigley *et al.* (2009) proposed detailed guidance for hydrologic, hydraulic, and water quality monitoring at the site level. Regarding the water quantity, there is a consensus to consider that performance is expressed in terms of runoff volume reduction, peak flow reduction, or restoration of the natural flow regime (Poff *et al.* 1997). Concerning the water quality, treatment performance is expressed in terms of pollutant load removal. The pollutants considered can be different from one context to another. Total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), metals (Cd, Cu, Pb, and Zn), and polyaromatic hydrocarbons (PAHs) can be the elements considered more frequently (Birch 2012; Park *et al.* 2015; Revitt *et al.* 2017; Arocho-Irizarry *et al.* 2018; Hamel & Tan 2021). Micropollutants have also become of interest in the last decade (Vezzaro *et al.* 2011; Gasperi *et al.* 2014).

Some efforts can be reported regarding other aspects than hydraulic and treatment performance. Several authors have considered cost-effectiveness via a cost analysis (Taylor 2003; Lee *et al.* 2010; Li *et al.* 2021). Duffy *et al.* (2008) conclude that SUDS are more cost-effective based on a whole-life costing analysed than traditional sewers. A relatively popular theme are environmental aspects such as the heat island effect and air quality (Norton *et al.* 2015; Zölch *et al.* 2016; Jayasooriya *et al.* 2017; Bartesaghi Koc *et al.* 2018; Saaroni *et al.* 2018), where urban green infrastructures are demonstrated to contribute to urban heat mitigation. Bianchini

Figure 2 | Example of stormwater management infrastructure where the main function is not related to water management: (a) street furniture (Melbourne, Australia), (b) roof (Burnley, Australia), (c) public park (Paris, France), (d) parking lot (Villeurbanne, France), (e) soccer field (Villeurbanne, France), and (f) pedestrian or cycle path (Villeurbanne, France). Photo credit: Frederic Cherqui.

& Hewage (2012) focused on the management of resources by performing a life cycle analysis of green roof material. Publications on public health and social aspects of BGI typically acknowledge the relevance of these aspects, while suggesting that further research on these aspects is needed (Tzoulas *et al.* 2007; Abraham *et al.* 2010; Cherqui *et al.* 2013; Austin 2014; Ely & Pitman 2014).

To date, assessing the holistic performance of BGIs through a composite indicator-based model remains a major challenge. Some recent initiatives are trying to address this issue, such as Al-rubaei (2016), Gordon *et al.* (2018), Meerow *et al.* (2021), Sørup *et al.* (2019), Staddon *et al.* (2018), Taylor *et al.* (2006), and Wang *et al.* (2019). For example, in one of the most comprehensive studies, Pakzad & Osmond (2016) proposed a conceptual framework that assesses green infrastructure performance employing 30 qualitative and quantitative indicators. These indicators address the ecological, health, socio-cultural, and economic aspects of BGIs. Nevertheless, some of the objectives of BGIs, such as resilience or contributing to climate-proofing, are still hard to evaluate.

Moreover, the large number of tree and plant species, each having specific maintenance requirements, can be a challenging issue for city councils to perform the maintenance process. Since the manual inspection of BGIs is time-demanding and inefficient, modern methods can be adopted. High-tech monitoring methods consist of wireless sensor networks to keep track of soil moisture, temperature, light, humidity, and pressure (Le *et al.* 2019), application of internet of things (IoT) systems (Lv *et al.* 2019), low-cost monitoring (Cherqui *et al.* 2020), real-time controls (Lewellyn *et al.* 2016; Xu *et al.* 2020), plant-/tree-based sensors, such as sap flow probes (Jones 2019), and unmanned aerial vehicles (UAVs) (Perc & Cirella 2020). Nevertheless, employing these methods has some challenges like the need for frequent monitoring and high maintenance and requires specialized personnel with specific technical skills.

Condition 2. The controller has a model of the controlled system

The last decade has seen the emergence of guidelines dedicated to stormwater control measures (http://tiny.cc/guidelinesSCMs). These guidelines are dedicated either to a specific infrastructure (e.g. wetland, bioretention system, porous pavement, and green roof) or provide more general recommendations for 'green infrastructures' or 'stormwater management' or 'water-sensitive urban design'. All these infrastructures have one point in common: they are complex as they include both grey and green elements and interact with the city and its inhabitants. Most guidelines give very general recommendations related to either the grey part (e.g. filter media and civil components) or to the green part (vegetation) such as removing litter or sediment, inspecting for physical damage, cleaning inlet and outlet points, flushing the underdrain, inspecting plant health, removing weeds, and mowing and replacing dead plants. These recommendations often provide frequencies associated with each action. They offer, however, limited knowledge to the field operators because they are not sufficiently specific (e.g. definition of physical damage or a blocked inlet), and it is difficult to assess if the recommendation applies to the specific local context. The limitations are strongly related to the fact that there is still a great need for a better understanding of these complicated systems to justify the actions and to adapt them to the context.

Two major barriers explain the lack of models or comprehensive guidelines. First, most BGIs combine grey (built) and green (natural) components. Assessing the performance of the grey components requires, among others, very specific expertise in hydraulics and civil engineering. But the performance assessment of green elements can require expertise in terrestrial, aquatic, or riparian ecology. Therefore, the overall assessment relies on a multidisciplinary approach, as is the choice of the best-suited rehabilitation actions. Moreover, the consequences of rehabilitation might not immediately follow the actions: if some actions are related to the growth of the vegetation, the benefits can have a delay of several months depending on the growth season. The second difficulty is related to the unicity of each asset. Compared to the traditional solutions such as pipes, each BGI is unique in terms of size, form, composition, and service delivered, and thus requires a unique model. BGI can have the following components: runoff surface or inlet, sediment or litter trap, filter media, monitoring system, flow control system, fauna, flora, retention volume, and protection structure. Figure 3 presents a fictitious BGI combining many of these components. It is a fictitious representation because almost all assets have a limited number of components. Each component requires specific O&M actions: all the components have their specific failures leading to adverse consequences regarding service functions (as presented in the previous section). A recent project (Vollaers *et al.* 2021) revealed that failures can occur within components but especially on the interfaces where responsibilities go from one actor to the next.

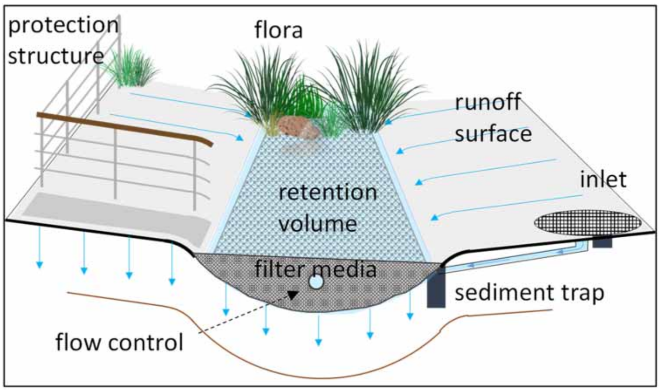


Figure 3 | Fictitious stormwater control measure including possible components (Credit Hélène Kaminski & Fanny Vanlerberghe).

It is worth mentioning that some guidelines, such as those proposed by Seattle Public Utilities (2019), suggest a scale of three to five levels of service with detailed descriptions and images for each level that helps determine by visual inspection whether recommended maintenance activities are needed. Browne *et al.* (2017) propose also a refined scoring system to rank and prioritize each asset to develop a maintenance and budget plan. The scoring system considers (i) the condition of the asset with respect to its impact on three factors (function and stormwater quality treatment, risk, and amenity) and (ii) the relative value and importance of the asset based on three factors (significance of the asset, catchment risk, and sensitivity of downstream receiving environment and visibility). Such initiatives are leading in the right direction, with the difficult balance between a methodology providing an exhaustive assessment of each asset and limited resources available for the inspection and assessment of each asset. More monitoring is required to better understand the medium- to the long-term behaviour of these assets and to be able to identify relevant failure mechanisms. It will provide the data required to build up-to-date and accurate enough models, and it should lead to better anticipation of failures and their consequences. The latter is required to shift from a run-to-failure approach to proactive management. In addition, the availability of robust data on Green Stormwater Infrastructure performance can be an incentive for municipalities wanting to adopt green, rather than grey approaches to stormwater management. At the same time, low-cost technologies are opening new potentials for the monitoring of assets with miniaturization and falling costs, allowing better spatial and temporal resolution. Such technologies can be the start of this 'out-of-the-box thinking'.

Condition 3. The controller has information about the environment and the controlled system

Information about the condition and performance of a system is essential to apply any asset management approach. This information about the environment and the controlled system can be difficult to obtain for non-piped systems either due to their inaccessibility (in case of underground infiltration facilities) or the difficulty in defining and measuring a proxy for condition or performance. Regular inspection techniques and schemes (Woods Ballard *et al.* 2015; Apt *et al.* 2019) in practice are still mainly focusing on visual inspection for NBS. Quantitative measurements of performance and condition indicators are mainly carried out for research purposes and have not found their way into daily BGI management yet (Boogaard 2022). This conundrum is also reflected in the guidance documents that exist, where routine inspections are described as mainly visual (checking for blockages, vegetation growth, and unwanted ponding; Rombout *et al.* 2007), while, on the other hand, the goal should be to establish ongoing performance assessment of hydraulic, water quality, amenity, and biodiversity performance of the system (Woods Ballard *et al.* 2015).

In contrast to piped networks, where standards on the condition assessment of systems exist (e.g. EN 13508-2 2011), the authors are not aware of a comparable guideline for BGI. Apt *et al.* (2019) give guidance about inspections throughout the life cycle of the BGI, from the construction, commissioning, to the operational phase in which an annual inspection is essential to ensure adequate maintenance and function. Also, inspection after significant storm events is recommended. For ponds and wetlands, typical inspection/maintenance frequencies are recommended (EPA 2009), and a level of inspectors' skill for the individual tasks is defined. The inspections are mainly connected to checklists which should be concise, specific, objective, and quantitative. Where possible it should also track the function of the BGI over time, but, in practice, the objectivity and quantification are of varying quality, which in turn makes it difficult and therefore seldomly done. Moreover, Lindsey *et al.* (1992) emphasized that greater consideration has to be given to bureaucratic processes that govern inspection implementation and political processes that determine fund availability.

As visual inspection of pipes often provides insufficient information about the structural condition of a pipe (Tscheikner-Gratl *et al.* 2019), the visual inspection of BGI can provide subjective and limited information about the performance of these systems. Autuori *et al.* (2019), for example, proposed a framework for the assessment of BGI performance encompassing risk reduction, technical and feasibility aspects, environmental, societal, and economic impact. While there is a manifold of performance indicators included in the design phase as part of a cost–benefit analysis, the evaluation of those indicators is mainly based on the assumption of a perfectly functioning system and not a time-dependent performance in a long term. This gap in research but even more in practice was already pointed out by Blecken *et al.* (2017).

Performance indicators are often reduced to hydraulic and water quality issues, when measured in research (Eckart *et al.* 2017), although Dhalla & Zimmer (2010) also give indicators for aquatic biology (e.g. index of biotic integrity) and terrestrial natural heritage (e.g. vegetation communities). The most common parameter to measure in infiltration-based BGIs is saturated hydraulic conductivity as a measure of infiltration capacity in the system (Ahmed *et al.* 2014; Paus *et al.* 2016). From a wider water quality perspective, most of the research has been conducted on the performance with respect to nutrients, metals (total and dissolved), and organic compounds. However, mostly on new or relatively new facilities and as part of research campaigns (LeFevre *et al.* 2015) as performing detailed monitoring would be too cost-prohibitive to be part of regular performance assessment programmes. Some more recent research has looked into the performance of ageing BGI (Johnson & Hunt 2020). However, again it is research-driven and not part of standard performance assessment. There is a strong need to develop standard performance assessment methods for BGI, methods that are simple to apply in the field while surveying the key parameters for performance assessment.

Even for those often measured and modelled parameters, the time dependency of the performance is seldom considered and highlighted. A few studies show a significant risk that existing stormwater infiltration systems in the field are working inadequately (Al-Rubaei *et al.* 2015). It has also been observed that permeable pavement system infiltration rates decrease significantly over time and that municipalities should plan to undertake maintenance around 10 years of continuous use (Boogaard *et al.* 2014). Brown & Hunt (2012) compared the overflow volume and pollutant loads of clogged bioretention cells before and after their maintenance. The overflow volume decreased from 35 and 37% in the pre-repair state to 11 and 12% after maintenance. Nearly all effluent pollutant loads exiting in the post-repair cells were lower than their pre-repair conditions. De Macedo *et al.* (2017) showed that average hydraulic retention efficiency increased from 66 to 86% after rehabilitation.

However, these only address three of the 17 benefits attributed to NBS by Woods Ballard *et al.* (2015), namely water quality improvement, increased sewerage system capacity, and flood risk reduction. And even for these uses, an individual system focused on performance assessment (e.g. peak flow reduction) might not be sufficient in an asset management approach because of the interconnection with existing (piped) urban drainage systems. The performance of the system regarding the other benefits, for example, urban bioclimate (Back *et al.* 2021), can change over time due to interdependencies between them and even have adverse effects on the rest. For example, increased biodiversity in plant life can affect the infiltration capacity and thus the hydraulic performance; or planting a single, fast-growing, short-lived species can capture carbon as an NBS benefit to climate change but has little potential to store that carbon over the long term (Cohen-Shacham *et al.* 2016). This restriction makes the claimed benefit of NBS of enhancing biodiversity partially non-quantifiable. Moreover, actual guidelines (Wood Ballard *et al.* 2015) do not provide standardized methodologies for such quantification. An intrinsic growth of biodiversity is beneficial, but the presence of invasive plant species needs to be controlled. A study carried out by Hitchmough & Wagner (2013) concluded that yearly maintenance (including irrigation in dry periods) is necessary to control the plant communities present in supra-urban drainage swales and avoid the presence of invasive or deep-root species. However, an increase in plant diversity might lead to an increased presence of soil fauna, mainly invertebrates. Indeed, Kazemi *et al.* (2011) proved that the presence of invertebrates was higher in bioretention swales compared to lawn-type green areas in Australian urban zones. Measuring the presence of invertebrates can be used as an indicator of biodiversity. However, the high presence of invertebrates (especially earthworms or beetles) can result in a reduction of removal efficiency because of their active role in soil and sediment bioturbation and their influence on the availability of pollutants

(Leveque *et al.* 2014). So far, the question on how the presence of macro- and micro-invertebrates affects the efficiency of BGI remains still open.

Amenities like the recreational usage of systems can influence the need for cleaning and maintenance. Nonetheless, how these changes occur over time is an open question. It is also a difficult question as the evaluation of these benefits requires a holistic approach, considering the whole range of benefits provided by different types of NBS and the interactions between them, together with the different spatial scales at which these can be relevant (Baró & Gómez-Baggethun 2017).

Condition 4. The controller has sufficient control actions to cope with the variability of the system

For sewers, operators have a large number of well-known control actions to deal with issues such as blockage affecting the hydraulic performance, where cleaning can be applied, or cracks affecting the structural integrity, where short-liners can be carried out. The control actions for sewer systems are well described in books and manuals, such as Stein (2001), WRc (2001), and Almeida *et al.* (2015). For BGI, this is less obvious. Regular maintenance, such as street sweeping for permeable pavement or mowing for swales, is often part of the general maintenance of public spaces, which is typically focusing on minimizing inhabitants' complaints rather than focussing on the hydraulic performance of the BGIs (Houle *et al.* 2013). Table 3 gives an overview of available control actions for common BGIs related to their hydraulic performance only. Control actions specifically aiming at maintaining other functions and benefits, such as recreation, education, or visual enhancement (Woods Ballard *et al.* 2015), have not been considered in Table 3 but should be part of maintenance strategies of BGIs in practice. Further research is required to assess how control actions for hydraulic performance align, or conflict, with control actions aiming at the broad range of functions of BGIs as discussed in the section on condition 1.

A recent review (Blecken *et al.* 2017) showed that stormwater control measures are often not maintained properly or even not maintained at all, resulting in early loss of their infiltration, treatment, or storage capacities. The authors illustrated the lack of attention to maintenance by the simple observation that a large proportion of stormwater control measures were simply not even accessible for inspection and cleaning. For permeable pavement, regular maintenance is essential to avoid clogging to an extent that milling and replacement of the top layer become necessary (Winston *et al.* 2016; Danz *et al.* 2020). Winston *et al.* (2016) also report that cleaning is often insufficient to restore the initial infiltration capacity.

The lack of attention to maintainability during design and construction and maintenance during service has regularly resulted in a situation where the operator has to learn by doing (Houle *et al.* 2013), sometimes leaving no other option than to replace the BGI to restore the hydraulic performance. Although the replacement costs, compared with piped systems, are relatively low, their presumed significantly shorter service life (10–30 years compared to 60–100 years) negatively affects the annual costs, while the fate of the pollutants captured in the BGIs during their service life has not received much attention in literature yet (McLaughlin *et al.* 2016).

Condition 5. The controller has sufficient information processing capacity to transform incoming information into effective control actions that are in line with the objectives

BGIs are often applied on a small scale. As a consequence, some solutions such as vegetated roofs, infiltration wells, or rain gardens can be implemented in private land typically on a household level. In that case, O&M must be taken care of by the house owner or the tenant who thereby becomes the controller. As O&M requires the capability to interpret current performance and to address signals of various kinds to predict future performance or maintenance needs, the level of complexity of the BGI easily goes beyond the capacity of the controller. Some studies focus on household take-up of BGIs at the individual scale, particularly in connection with incentive programmes intended at providing financial or technical assistance implemented by utilities (Ando & Freitas 2011; Ward *et al.* 2013; Baptiste *et al.* 2015; Brown *et al.* 2016; Coleman *et al.* 2018; Shin & McCann 2018; Yu *et al.* 2019; Drescher & Sinasac 2021). But the obstacles that prevent households from adopting these solutions are yet to be better identified (Coleman *et al.* 2018). The question of the role of users in predicting future performance and maintenance needs also remains open while it would seem important to pay attention to their vision of the evolution of their own needs in the face of global change.

More broadly, this calls for a better understanding of the roles inhabitants could play in the O&M of BGIs implemented in a public place and of the place to be given to their preferences. They could, for instance, play an active role in malfunction detection, just like the 'Adopt a drain' initiatives developed in the USA (https://regions.adopt-a-drain.org/). With regard to residents' preferences, some studies assess the perception of benefits

Table 3 | Control actions for BGIs

Type of system	Degradation mechanism	Control action
Wet pond/wetland	Sedimentation resulting in storage loss and pollutant accumulation in the sediment bed Vegetation overgrowth	Dredging Removing/mowing
Vegetated filters	Surface clogging	Reconstruction and replanting
Grassed swale/filter strips	Loss of infiltration capacity Accumulation of pollutants in the top layer Runoff blockage due to road subsidence, turf growth, and sediment accumulation	Renew top layer Removal of the top layer Restore road level and removal of the top layer of turf and sediment
Green roof	Vegetation loss Vegetation overgrowth	Vegetation upkeep
Infiltration trenches	Clogging	Removal of the top layer, removal of sediment
Permeable pavement	Clogging	(Vacuum) cleaning, high-pressure washing, milling, and replacing the top layer

provided by BGI and estimate inhabitants' willingness to pay for their implementation. However, they generally focus on a specific solution rather than on a patchwork of BGIs (Clark *et al.* 2008; Zhang *et al.* 2019), and they generally focus on a specific benefit rather than on a patchwork of (co-)benefits, this benefit most often being the capacity of BGI to help control floods (Zhai *et al.* 2007; Londoño Cadavid & Ando 2013; Wang *et al.* 2017; Zhang *et al.* 2019), with the notable exception of Brent *et al.* (2016) and Rulleau (2018). The perceptions of dis-amenities are even less investigated (Williams *et al.* 2019), even though in some cases BGI has been shown to negatively affect the price of nearby homes (Irwin *et al.* 2017). Cost–benefit analysis might prove particularly useful in helping understand more about the pros and cons of implementing BGI and provide insight and information which can be integrated into public decision-making (Rulleau & Werey 2019).

BGIs are often presented as a way to handle nature and quality of life, particularly in the vicinity of urban centres. However, the existing literature almost exclusively studies the conditions of their implementation that maximize the co-benefits (Dagenais *et al.* 2017) or the relationships between their implementation and a selection of socio-demographic variables (Wendel *et al.* 2011; Mandarano & Meenar 2017; Baker *et al.* 2019). These studies only question the effects on individuals through motivations or arguments related to landscape and the living environment. The issues of their spatial distribution remain unaddressed, especially in connection with social and environmental justice issues (Dunn 2010; Haase *et al.* 2017). Furthermore, as shown by Venkataramanan *et al.* (2019), studies focus on the impacts of BGI under a specific aspect of well-being (economic, social, or physical, or mental health).

Finally, the question of the collective appropriation of BGI remains open. These solutions are not always well accepted by practitioners (Thurston *et al.* 2010; Cettner *et al.* 2013, 2014; Matthews *et al.* 2015; O'Donnell *et al.* 2017; Bissonnette *et al.* 2018) or stakeholders (Comby *et al.* 2019), including the general population (Londoño Cadavid & Ando 2013; Penn *et al.* 2014; Nurmi *et al.* 2016; Derkzen *et al.* 2017; Williams *et al.* 2019). In other words, this relates to the way residents and users of public space appropriate these infrastructures and the support provided by public authorities to do so. It also means investigating the positioning of decision-makers to clarify the motivations and strategies behind the use of BGI (Cousins 2017) and the choice to adopt one rather than another. By extension, this suggests to address public action processes when it comes to BGI (Matthews *et al.* 2015). These issues are all the more important that, as previously discussed, many actors and services are involved in the design, implementation, monitoring, and maintenance of stormwater management green systems (Chaffin *et al.* 2016; Dhakal & Chevalier 2016; Mandarano & Meenar 2017).

APPLICABILITY OF TRADITIONAL ASSET MANAGEMENT TO BGI

The applicability of the concept of asset management to BGI has been assessed by evaluating whether the five preconditions for effective control can be met. Table 4 provides an overview of the main findings by comparing the situation for sewer systems and BGI. Clearly, the current state of the art in O&M is insufficient to translate sewer asset management concepts into concepts for BGI as none of the conditions for effective control is (fully)

Table 4 | Overview of findings

Condition	Sewer systems	BGI
1. Clear objective and evaluation mechanism	Well-established with respect to the condition assessment of pipes and less established with respect to the sewer system performance	Hampered by the large diversity of criteria, which are only partly quantifiable
2. Model of system	Well-established for hydraulics and less established for asset deterioration	Models describing BGI performance and condition deterioration are very limited
3. Information on environment and system	Well-established standards	Strongly lacking
4. Sufficient control actions	Widely available via textbooks and manuals	Limited availability of control actions for restoring condition and performance
5. Sufficient information processing capacity to select effective control actions	Utilities (or their contractors) have sufficient capacity to process inspection and monitoring data and to select effective measures	The diversity of involved actors and the broad range of aspects to be taken into account result in difficulties in selecting appropriate actions

met, which is partly due to inherent difficulties in matching the controlled system, the infrastructure, with a dedicated controller. For sewer systems, the utility is typically the controller, while, for BGI, the situation may be rather ambiguous. Depending on the situation, inhabitants, property owners, different departments of the municipality, or a water utility could act as a controller or sometimes even as a co-controller controlling only a subset of components or functions of the BGI. Unclear, divided or shared responsibilities could be problematic with respect to maintenance, while the large diversity in responsible actors (controllers) does not facilitate easy uptake of novel approaches.

CONCLUSIONS AND OUTLOOK

The confrontation of the state of the art on management practices and knowledge of BGIs revealed that asset management of BGIs is still underdeveloped, in practice resulting in (unnoticed) underperformance and degradation of BGIs. Confronting the state of the art of BGI asset management with the five preconditions for effective control revealed, listed per condition, that:

- Evaluation mechanisms for checking the performance of BGIs are insufficient to cover the large variety of services BGIs deliver. Basic knowledge of these services is available but not enough yet to provide a holistic assessment.
- Models describing BGI deterioration and the evolution of BGI condition are limited, partly due to a lack of monitoring, but also because each BGI is in essence a unique system embedded in the urban environment.
- Information about the condition of BGIs and about their environment is lacking strongly: most of the BGIs are not or only seldomly monitored. When monitored, the almost exclusive type of investigation is visual inspection without a recognized framework to evaluate inspection results.
- Control actions helping restore the condition and performance of BGIs are limited. For some BGIs, such as infiltration facilities, only complete rehabilitation of the top layer is available as control action.
- Decision-making and taking actions are difficult due to (i) the location (private/public) and the required coordination (between inhabitants and the different departments of the local authority) and (ii) the general lack of guidance for proper O&M. Furthermore, the definition of the expected service life that has a major influence on the economic assessment is based on little data and would need reassessment.

Compared to sewer asset management, the asset management of BGIs is far from being operational. BGIs will, however, continue to be increasingly deployed worldwide because they provide answers to our societal needs. Today, the situation is becoming critical, mostly because their management needs and long-term performance remain unknown. Because this critical situation being acknowledged, and thanks to the methods and knowledge developed for sewers, the learning curve can be much faster than the decades it took to develop sewer asset management. This development is supported by the revolution happening in low-cost monitoring, miniaturization, easy-to-access, modularity, and open-source programming (Cherqui *et al.* 2019a, 2019b). The remaining key challenges for the research community are dealing with the diversity of solutions and conditions, the lack of a common framework to assess the delivered services, lack of knowledge on the effectiveness of available O&M options on the scale of potential services and the lack of resources to conduct dedicated, long-term research on full-scale BGIs including their interactions with their surroundings. This is very important, as BGI performance and failures strongly interact with the end users. Although desktop studies and lab studies may help address individual failure mechanisms, research on full-scale real-world BGIs is necessary to develop the required knowledge to be able to benefit from asset management for BGIs. The starting point for this research would be to collect, document, and analyse the hands-on experience of the practitioners involved.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 13 September 2022; accepted in revised form 27 November 2022. Available online 7 November 2022