An analysis of the understanding of maintenance of nature-based solutions for urban stormwater management

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Abstract

Urban stormwater management is necessary to protect human life and society from the dangers and damages associated with flooding from extreme weather events. Conventional measures of stormwater management utilise grey infrastructure to convey runoff away from urban areas, but due to increasing urbanization, aging of urban infrastructure, climatic variability, and flooding due to extreme weather events, these measures are often no longer sufficient. On the other hand, sustainable stormwater management systems, such as nature-based solutions, involve working with ecosystems in order to improve resilience and adaptability in a changing climate, while simultaneously providing other benefits to biodiversity, pollution control, and human health.

While academic interest in sustainable systems, and the transition from conventional measures in urban areas, is growing, there remains significant uncertainty surrounding the maintenance of these systems. To investigate the maintenance requirements, how it impacts the transition, and how to reduce this uncertainty, a comprehensive literature review was undertaken, analysing 70 texts on the subjects of urban stormwater management, nature-based solutions, and maintenance.

The findings indicate a variety in terminology and concepts used to describe sustainable systems, causing confusion, and resulting in fragmentation of the body of knowledge of them. Data on maintenance activities, frequencies, and costs for both conventional and sustainable systems were compiled. Major barriers discovered include unclear management responsibilities, lack of expertise, misconceptions regarding maintenance demands, uncertainty in long-term costs and performance, and a lack of policy and governance instruments.

Collaboration and education will be vital to expanding the transition to sustainable stormwater management. Incorporating maintenance and stakeholder involvement throughout the planning process will reduce the uncertainty involved in the implementation of nature-based solutions. Large-scale and in-depth monitoring and reporting programs will provide evidence in performance and lifespan and reduce uncertainty further. Educating decision-makers and the public alike on the efficacy and benefits of nature-based solutions will lead to wider acceptance. Strong regulatory and governance frameworks will foster widespread uptake, encouraging the transition from conventional to sustainable urban stormwater management.

Keywords

Flood adaptation, resilience, sustainability, green infrastructure, uncertainty.

Sammanfattning

Stads vattenhantering är nödvändigt för att skydda människors liv och samhällen från de faror och skador som är förknippade med översvämningar från extrema väderhändelser. Konventionella åtgärder för dagvattenhantering använder grå infrastruktur för att föra bort avrinning från stadsområden, men det finns allt fler bevis för att dessa åtgärder inte längre är tillräckliga. Däremot innebär hållbara dagvattenhantering system, såsom naturbaserade lösningar, att arbeta med ekosystem för att förbättra motståndskraft och anpassningsförmåga i ett föränderligt klimat, samtidigt som det ger andra fördelar för biologisk mångfald, föroreningskontroll och människors hälsa.

Medan det akademiska intresset för hållbara system och övergången från konventionella åtgärder i stadsområden växer, finns det fortfarande betydande osäkerhet kring underhållet av dessa system. För att undersöka underhållskraven, hur det påverkar övergången och hur man kan minska denna osäkerhet, genomfördes en omfattande litteraturgenomgång som analyserade 70 texter om hantering av dagvatten i städerna, naturbaserade lösningar och underhåll.

Fynden indikerar en variation av terminologi och begrepp som används för att beskriva hållbara system, vilket orsakar förvirring och resulterar i en delad brist på kunskap. Data om underhållsaktiviteter, frekvenser och kostnader för både konventionella och hållbara system sammanställdes. Stora hinder som upptäckts inkluderar otydliga ledningsansvar, bristande expertis, missuppfattningar om underhållskrav, osäkerhet i långsiktiga kostnader och prestanda samt brist på policy- och styrinstrument.

Samarbete och utbildning kommer att vara avgörande för att utöka omställningen till hållbar dagvattenhantering. Att inkludera underhåll och engagemang från intressenter under hela planeringsprocessen kommer att minska osäkerheten i implementeringen av naturbaserade lösningar. Storskaliga och djupgående övervaknings- och rapporteringsprogram kommer att ge bevis för prestanda och livslängd samt minska osäkerheten ytterligare. Att utbilda såväl beslutsfattare som allmänheten om effektiviteten och fördelarna med naturbaserade lösningar kommer att leda till en bredare acceptans. Starka ramar för regelverk och styrning kommer att främja en bred spridning, och uppmuntra övergången från konventionell till hållbar hantering av dagvatten i städerna.

Nyckelord

Översvämnings anpassning, spänstighet, hållbarhet, osäkerhet.

Acknowledgements

Firstly, I am extremely grateful for my advisors, Luigia Brandimarte and Mark Usher, for their advice, comments, and guidance throughout the research process. Their engagement and encouragement have been invaluable during this experience. I would also like to thank Evie Merrygold, another student working on the project, for her assistance during the data collection and research stage, as well as her availability for discussion and collaboration throughout the process. Finally, my appreciation goes out to my family and friends for their encouragement throughout this master thesis and all my studies.

Table of Contents

Abbreviations

ASCE – American Society of Civil Engineers

BGI – Blue-Green Infrastructure

BMP – Best Management Practices

CIRIA – Construction Industry Research Information Association

GI – Green Infrastructure

IUCN – International Union for the Conservation of Nature

LID – Low-Impact Development

NBS – Nature-Based Solutions

NNBF – Natural and Nature-Based Features

NOAA – National Oceanic and Atmospheric Administration

O&M – Operations and Maintenance

SC – Sponge City

SCM – Stormwater Control Measure

SSM – Sustainable Stormwater Management

STP – Stormwater Treatment Practice

SUDS – Sustainable Urban Drainage System

SUWM – Sustainable Urban Water Management

US ACE – United States Army Corps of Engineers

US BR – United States Bureau of Reclamation

US DOT – United States Department of Transportation

US EPA – United States Environmental Protection Agency

WSUD – Water Sensitive Urban Design

1 Introduction

Of all weather-related disasters, floods are the most frequent and the most damaging (World Bank, 2017). Around the world, extreme weather events leading to flooding have led to loss of life and billions of dollars in damages. In 2011, flooding in Japan lead to 15,000 fatalities, and in Thailand, resulting in losses of over US $45 billion (Jonkman & Dawson, 2012). Between 2006 and 2015, urban flooding impacted approximately 140 million people worldwide (Huang et al., 2020). In 2017, global losses exceeded US $300 billion, and is projected to increase in the coming decades (Jongman, 2018). With more than half the global population now living in cities, and urbanization still increasing, the impacts to society are severe (Huang et al., 2020). Our capacity to manage urban flood risks is consequently of vital importance.

Urban flood management is critical for safety, health, and to protect against damage. The impervious nature of much of the surface area of cities prevents drainage back into the natural water cycle, leaving runoff to accumulate and leading to flooding. Much of conventional drainage systems focus on the function of moving as much water away from areas where people live as possible, as quickly as possible (Huang et al., 2020). By concentrating on transporting runoff away, rather than retaining and managing at the source, many flood risks are simply pushed downstream: excess runoff flows into downstream areas and increases as it goes (Woods Ballard et al., 2015).

While conventional urban drainage systems have been standard and extensive in urban regions for many decades, and therefore knowledge of the requirements of such systems are well-known, recently it had become increasingly clear that they do not have the flexibility or resilience to deal with the uncertainty that comes with climate change (Emilsson & Ode Sang, 2017). In countries known for their flood risk management, such as the Netherlands, aging infrastructure means a lot of flood defense measures are not up to standards (Jonkman & Dawson, 2012). As well, stormwater management systems haven't increased along with urban population growth in many parts of the world (Huang et al., 2020). In answer to these issues, many places are turning away from conventional measures for stormwater management in favour of more sustainable ones.

Sustainable flood management schemes don't simply rely on capacity to convey stormwater, they also act to reduce the volume of runoff at the source. Typically, this involves a reduction or lack of impervious surfaces, to allow runoff to infiltrate and return to the natural water cycle before traveling through urban water infrastructure systems, and the incorporation of vegetation and ecosystem connections retain the properties of the pre-development ecosystem and hydrologic cycle (Woods Ballard et al., 2015). Natural systems also include other benefits, to biodiversity, ecosystem health, pollution removal, and more.

Nature-Based Solutions (NBS) are a concept that promote incorporating more natural processes in engineering design and projects. The European Commission defines NBS as "living solutions inspired by, continuously supported by and using nature designed to address various societal challenges in a resource efficient and adaptable manner and to provide simultaneously economic, social, and environmental benefits" (European Commission, 2015). This is a broad concept and therefore can applied to a wide variety of issues, including urban flood management. The lack of specificity in this definition can lead to ambiguity and confusion, and several other definitions have also been developed. For example, the IUCN has also defined NBS as "actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016). While these two definitions are broadly similar, there are some specific differences. The IUCN definition emphasises the importance of protecting and restoring natural systems, while the European Commission includes using nature in more engineered systems, and it also includes economic benefits as a pillar of sustainability, which the IUCN does not. However, NBS is

just one concept applied to sustainable urban flood management, and the lack of a strict definitional framework of NBS extends to the variety of other terms and concepts used across the world, which only adds to the confusion.

Stormwater management at the urban scale is traditionally handled through a combination of "grey" infrastructure including gutters, sewers, culverts, and detention basins (USEPA, 2022). Most of these components are impervious (i.e. made of concrete) and underground. The nature of urban areas includes extensive impervious surfaces, preventing the natural water cycle from proceeding after heavy rainfall events. When runoff encounters these impervious surfaces, not only can it not return to the water cycle, it also picks up various pollutants and contaminants as it travels. In some urban areas, the runoff from this system is discharged into surface water bodies such as rivers, while others are processed through a treatment facility before being discharged. In contrast, sustainable stormwater management is designed to reduce the volume and improve the quality of runoff (Erickson et al., 2013). There are 4 main processes that are utilised to achieve these goals: sedimentation, filtration, infiltration, and bioretention.

Sedimentation practices involve retaining volumes of runoff in wet ponds, dry ponds, or constructed wetlands (Erickson et al., 2013). They promote the natural settling of particles, which can then be removed. *Filtration* practices capture these particulate pollutants through a filter medium, usually sand. They are typically smaller than sedimentation ponds, usually used in drainage ditches along roads, parking lots, or other impervious surfaces, and don't have much retention capacity (Ellis et al., 2014). *Infiltration* practices are designed to capture, retain, and slowly infiltrate stormwater into the underlying and surrounding soil. Infiltration trenches and basins typically require pre-treatment bays to capture the majority of sediment and pollutants, for easier removal (Ellis et al., 2014). Permeable pavement breaks up the impervious surface area of roadways to allow for infiltration throughout (Erickson et al., 2013). *Bioretention* practices are vegetated areas that combine filtration and infiltration processes, with permeable soils and sand filters with a drain beneath to discharge the collected runoff (Erickson et al., 2013). These practices are used in rain gardens, green walls and roofs, and bioswales.

Several cities have attempted to incorporate NBS into urban stormwater management. Malmö, Sweden has a neighbourhood (Augustenborg) that is disconnected from the sewer system and handles stormwater locally (Haghighatafshar et al., 2018). Philadelphia, USA has replaced one third of their impervious surfaces with permeable pavements, green spaces, and other sustainable measures to control runoff from approximately 35% of the city's area (Fitzgerald & Laufer, 2017). Beijing is one of many cities participating in the Sponge City Project in China, designed to control up to 85 % of annual runoff (Lashford et al., 2019). However, widespread transition from conventional systems has been minimal (Green et al., 2021, Brillinger et al., 2021).

There are many studies and reviews investigating the challenges and barriers preventing this transition, and the uncertainties surrounding maintenance is often included as one of the major challenges (DelGrosso et al., 2019, Wright et al., 2022, and more). Maintenance is necessary for the continued performance and function of any system component, conventional or sustainable (Gibbons, 2016). However, the correlation between maintenance and performance is stronger for sustainable systems (DelGrosso et al., 2019), and yet their maintenance requirements as clear-cut as conventional systems, for several reasons. Firstly, because many components of conventional systems are underground, very little routine maintenance is needed due to exposure to the elements. This can also lead to an "out of sight, out of mind" approach to maintenance. In contrast, many sustainable practices and measures are above ground, which require more extensive land area and can therefore be an issue in dense urban settings (Sarabi et al., 2019). In addition, the design process for conventional systems is very well-established, and design choices can be made to reduce the maintenance needed of the life span, such as maintaining high enough velocities to prevent pipe blockages due to sediment deposition, and directing sedimentation to areas that are most convenient to access for

maintenance (Maidment, 1993, Quang et al., 2022). Finally, incorporating vegetation and natural ecosystems requires expertise of the local climate and ecological conditions, to choose the optimal species for the purposes of the system, which makes sustainable systems very context-specific, unlike conventional systems which are largely standardized.

It is becoming increasingly clear that conventional stormwater management systems cannot keep up with flooding caused by extreme weather events, rapid urbanization, and the aging of urban infrastructure. Incorporating NBS into urban stormwater management can counteract many of these issues, through retention, infiltration, pollutant removal, and vegetation practices. Investigating the transition to sustainable systems has attracted growing academic interest, but less attention has been paid to the ongoing maintenance of these systems, leading to uncertainty and a major barrier to incorporation in urban stormwater management. In order to understand the maintenance difficulties and reduce this uncertainty, this study involves a comprehensive literature review to analyse maintenance needs and challenges.

2 Aim and research objectives

The literature analysed in this report covers many topics: description of properties, definitions, and typologies of NBS, design, implementation, and maintenance guidance, performance, efficiency, and cost-effectiveness comparisons with conventional systems, barriers and drivers to implementation, case studies of attempted implementation, perceptions surrounding NBS and their maintenance, and the consequences of improper or inadequate maintenance.

Studies of performance and efficiency of NBS, such as Chen et al. (2019) and Haghighatafshar et al. (2018) confirm the effectiveness of NBS at controlling local pluvial flooding and reducing runoff volumes. Cost-effectiveness studies such as Naumann et al. (2011) and Vineyard et al. (2015) prove NBS can compete with conventional measures in economic aspects.

Dhakal & Chevalier (2017) and Esmail & Suleiman (2020), among others, investigate the policy and governance aspects of implementation, and how they inhibit the transition. They conclude that cities need strong regulatory and governance frameworks in order to overcome the reliance on and bias towards conventional systems.

Analyses of the barriers to NBS overwhelmingly conclude that uncertainties surrounding performance and maintenance of sustainable systems is a common barrier to more widespread implementation, such as Thorne et al. (2018), Sarabi et al. (2019), Macmullan (2007), and Qiao et al. (2018).

Investigations of perceptions of sustainable systems from public, private, industry, academic, and resident perspectives, such as Melville-Shreeve et al. (2018), Everett et al. (2018), Han & Kuhlicke (2021), discuss the importance of public support to the transition. Perceptions of sites as untidy and unmaintained, when they're so visible to residents, negatively impacts that support.

Improper or inadequate maintenance, resulting in disrepair and dysfunction, are studied by Wright et al. (2022) and Blecken et al. (2017), among others. Their conclusions indicate that continuous, adaptive, and design-appropriate maintenance is essential to maintain performance and longevity of NBS.

The gaps discovered in this literature include direct comparisons of maintenance planning and requirements between conventional and sustainable systems, how maintenance uncertainty impacts the transition, and what policy and governance instruments can be implemented to facilitate it. This report aims to investigate the uncertainty surrounding maintenance and how it impacts to widespread uptake of NBS in urban stormwater management. To that end, the following research objectives have been established:

- Consider how maintenance has been perceived, understood, and planned in respect to urban flood management, focusing on the differences and similarities in the maintenance processes between grey and green approaches.
- Examine the barriers, challenges, risks, and opportunities relating to maintenance, how they are impacting the transition from grey to green approaches, and whether or not there is effective integration in existing policy and governance arrangements.

3 Methodology and data collection

To respond to the research objectives, the following steps were taken.

1. data collection through a tailor-made literature scouting, to gather different sources of information (academic articles, technical standards and guidelines, handbooks, manuals) addressing purpose, design, and maintenance of stormwater management systems, as well as barriers, drivers, and policy and governance implications of sustainable systems.

2. data screening, to select most relevant literature from the collected data

3. data classification, to organize the collected data and uncover trends or common themes, and

4. data analysis, to understand the distribution of literature and to

3.1 Data collection

The first step of this review was data collection, using a variety of online literature databases and search terms. The search began with the term NBS, looking for the collection of literature on NBS as an umbrella term and then narrowing to the urban flood management field. From there, as more terms for similar concepts were understood, more search terms were incorporated. Figure 3-1 shows a flowchart detailing the progression of search parameters used in this literature review. Finally, a total of 70 articles, guidance documents, and reports were chosen for the review. The KTH library database, Google scholar, the NOAA Green Infrastructure database, the ASCE library, and the Wiley Interdisciplinary Reviews library are the search engines used for academic literature for this review, while for grey literature, authority websites, such as US EPA, were also used.

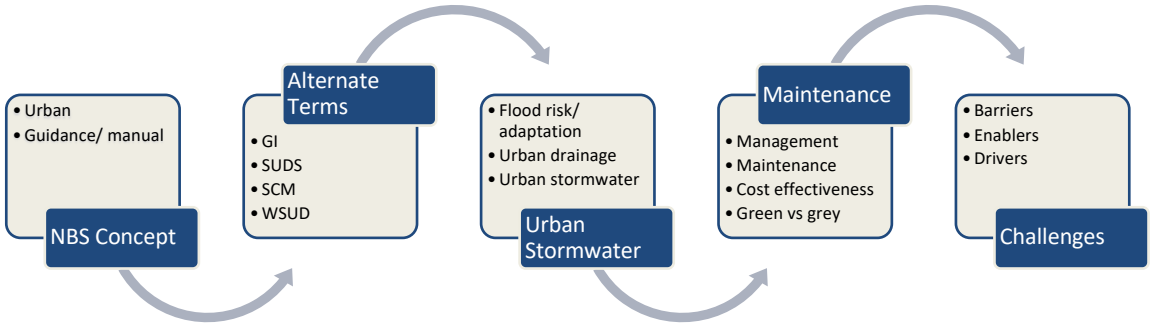

Figure 3-1 Flowchart conceptualizing the evolution of search terms

3.2 Data screening

In order to narrow the search results to the most relevant literature, screening was undertaken. While some of the general guidance documents included are not specific to urban NBS, many texts were excluded for focusing on coastal systems. When a text is focused on urban NBS, but included no mention of maintenance, it was also discarded. Another common reason was that the primary focus was on adjacent concepts without the inclusion of NBS such as climate change adaptation or ecosystem services.

3.3 Data classification

Once the final 70 papers were selected, the data was classified using an excel spreadsheet. In this way, the literature can be grouped based on location, year, type of literature (academic or grey), terminology used, or topic of discussion. Columns were filled in for each text according to the following topics: year, publication, location, terminology, system components included, summary of content, whether they discussed design and implementation guidance, maintenance, barriers or drivers to implementation, policy and/or governance, source, and search terms. Table 1 shows an example row from this spreadsheet, using one article (Huang et al., 2020). The full spreadsheet is included as Appendix A.

Table 1 Sample row, data classification spreadsheet (Appendix A)

Author	Year	Title	Publication/ Publisher	Type of literature	Location	Terminology
Huang et al	2019	Nature-based solutions for urban pluvial risk management	Wires Water	Academic article	China	**NBS**, SUDS, LID, BMP, WSUD, GI, sponge city

System components	Topic of Discussion	Content	Source	Search Terms
General, urban	Terminology, barriers, and benefits of NBS	Discusses the similarities & difference of terminology, concludes NBS tend to be less effective under extreme weather events, but much more effective in small-scale events	Wiley database	"Sustainable engineering of water"

3.4 Data analysis

The literature, once gathered, screened, and classified, could then be analysed. This is showcased in the results in the following section. First, an analysis was undertaken to understand the distribution of gathered literature, by country, by time, and by terminology. Following that distributive analysis, the content of the literature was analysed to fulfill the research objectives established. Major barriers, maintenance activities, frequencies, and costs, and policy and governance instruments were investigated.

4 Results and analysis

The literature review covers 70 papers; of those are 53 academic articles and research reports, and 17 grey literature publications – including industry reports, guidance documents, and textbooks. The literature includes assessments of NBS in fifteen countries: the USA, The UK, Sweden, Germany, the Netherlands, Portugal, South Korea, China, Indonesia, Canada, St Maarten, Brazil, Colombia, Ecuador, and Peru. Publication dates span from 1993 to 2022. Of the academic articles, 42 span 24 major journals, with the rest include a master thesis and several smaller journals and magazines. While NBS is the term chosen in this report to discuss sustainable urban stormwater management, the literature included the use of eight comparable terms, including NBS. This are detailed in Table 2 below.

Table 2 Terminology used across the literature

NBS	Nature-based solutions
GI	Green infrastructure
SUDS	Sustainable urban drainage system
BGI	Blue-green infrastructure
SCM	Stormwater control measure
WSUD	Water sensitive urban design
LID	Low-impact development
BMP	Best management practices

Figure 4-1 shows the breakdown of the literature by country. As the figure shows, the USA contributed the most to the literature, with 27 papers. The UK had the next most, at 13. Following this are Australia and Sweden with 7, China with 5, the Netherlands with 4, Canada and Germany with 2 each, and the rest (South Korea, Indonesia, Portugal, St Maarten, Brazil, Colombia, Ecuador, and Peru) each have one.

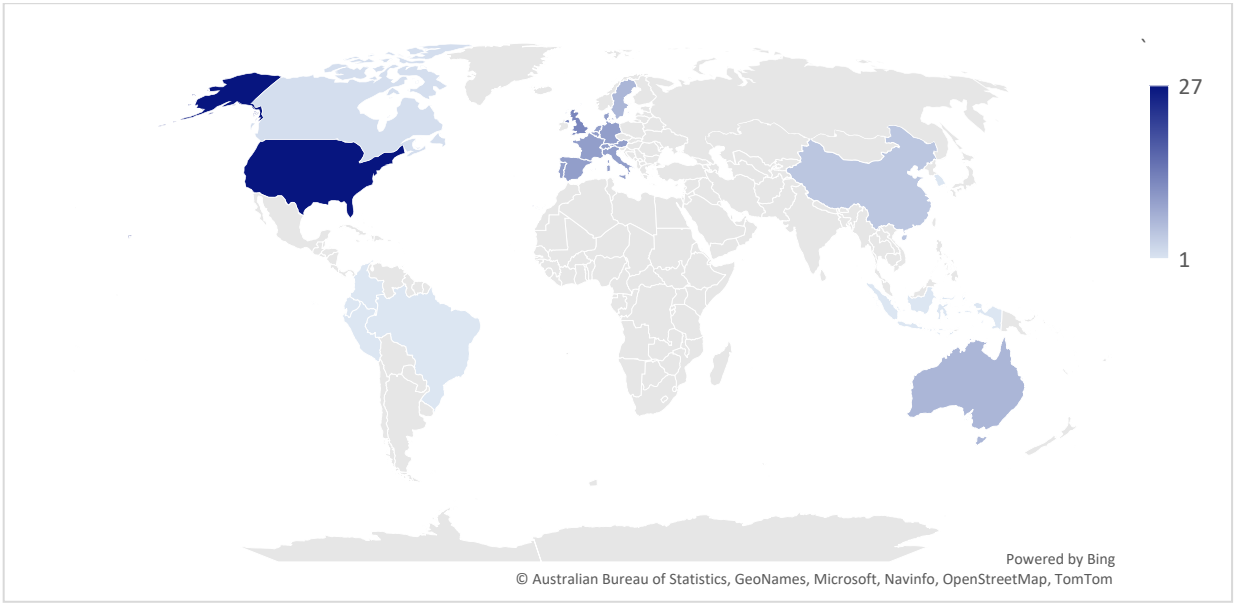

Figure 4-1 Literature breakdown by country

Figure 4-2 shows the breakdown of the literature over time. While there are a few texts from before 2010 (6 in total), they are inconsistent before that point. From 2016 to 2021 there are at least 5 texts each year, with the most (12) published in 2019.

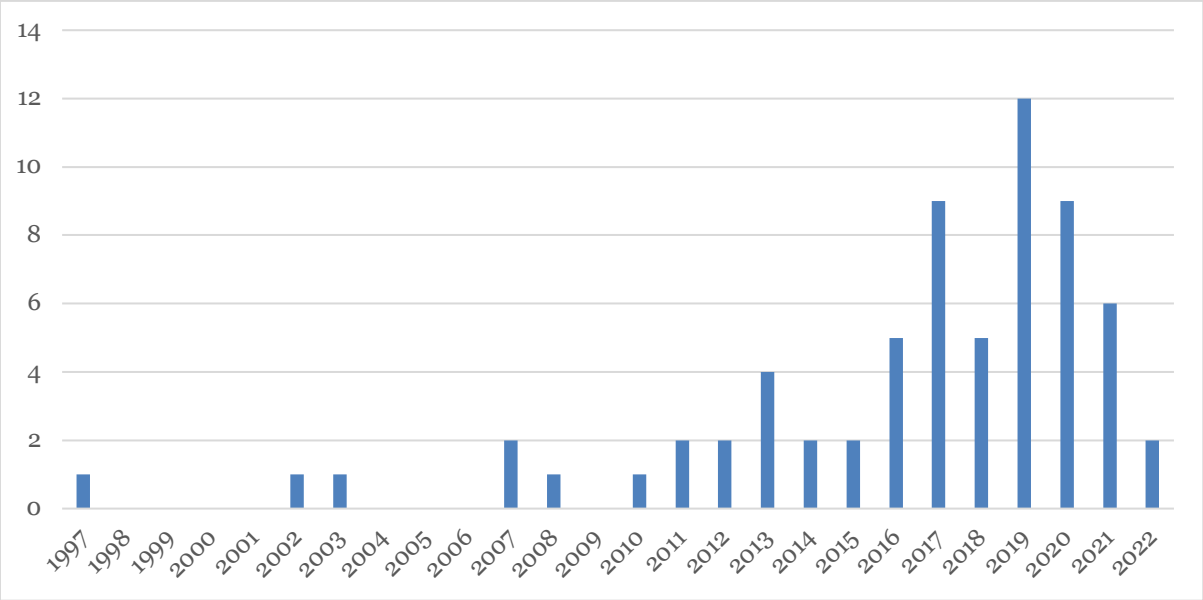

Figure 4-2 Article count over time

The following sections address the major points that were found during the analysis of all collected data. In particular, focus is put on 4 aspects that were considered relevant:

1) *terminology*, that is, the concept used to discuss sustainable urban stormwater management, and how the variety in terms used throughout the literature collected (see Table 2) causes or contributes to the complexity, confusion, and uncertainty that surrounds sustainable stormwater systems.

2) *major barriers* and challenges to maintenance, in order to understand how maintenance can hinder a wider uptake of NBS,

3) *comparison of maintenance* with conventional systems, and

4) *policy and governance instruments* either impeding or promoting sustainable systems.

4.1 Terminology

Over the course of the literature review, many terms and concepts were discovered and researched. In the final body of literature, eight main terms are used (Table 2), along with an "other" category. This category covers terms that the author established themselves, as well as terms with only a few uses. While all these terms are used by the authors to discuss sustainable stormwater systems, typically a single term is chosen for use throughout the paper, like NBS is used in this report. Figure 4-3 shows the portions of each of these terms.

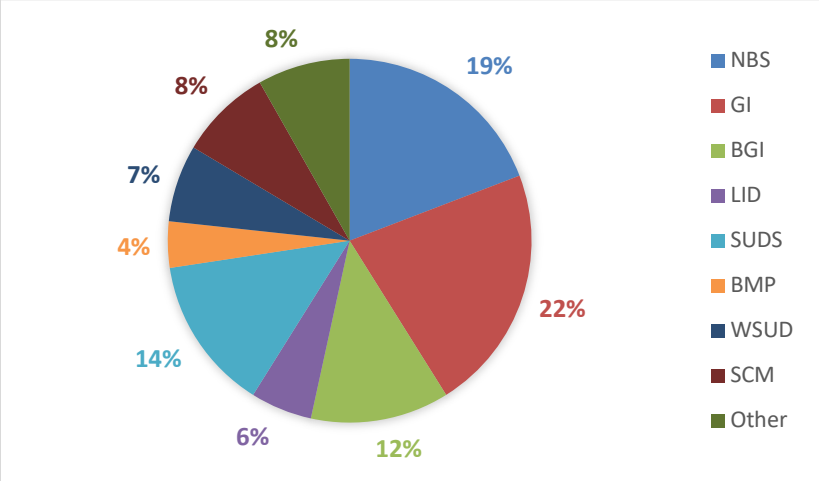

Figure 4-3 Literature breakdown by terminology

"Other" terms include Sponge City (SC) with two uses, and sustainable stormwater management (SSM), sustainable urban water management (SUWM), stormwater treatment practices (STP), and natural and nature-based features (NNBF) with one each. Across the literature, GI is used the most by a small margin, followed by NBS (16 and 14, respectively). Following these are SUDS with 10 and BGI with 9. The rest all have 6 or less.

Some terms are older than others. The first to be commonly used, at least in the United States, is Best Management Practices (BMP). The first mention of this term in the body of literature is from 1997. Terms are subsequently introduced as follows: Water Sensitive Urban Design (WSUD) – 2002, Low-Impact Development (LID) – 2007, Sustainable Urban Drainage System (SUDS) – 2008, Green Infrastructure (GI) – 2010, Stormwater Control Measure (SCM) – 2013, NBS – 2016, Blue-Green Infrastructure (BGI) – 2017. The trend over time of each of these terms is shown in Figure 4-4. This is not indicative of the first known uses of these terms in practice or in academia, just the first mentions in the current literature review.

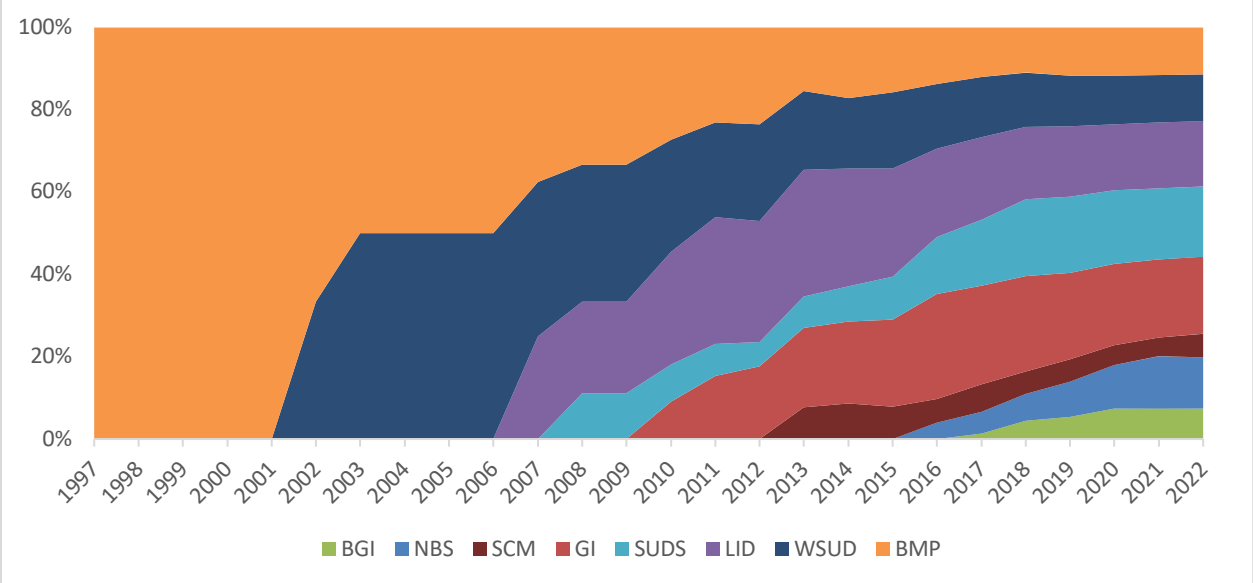

Figure 4-4 Terminology usage over time

Many articles use more than one term, or reference some of the other terms commonly used. While this adds to the terminology usage over time, most articles establish one "umbrella" term to be used throughout the text. Using this we can further break down Figure 4-2 among the terms used – this is shown in Figure 4-5. The figure shows that BMP and LID are some of the earliest terms included, but usage has dropped off more recently when compared to the other terms. By looking at this figure in combination with the previous, you can see that although BMP continues to be included, usually as alternative concepts in articles using a different term, it is not the chosen "umbrella" term after 2012. Similarly, LID is often included as an alternative, but not used as an umbrella term since 2017. As other terms have been established and gained popularity, these two have been left behind. NBS and BGI have entered usage the latest – in 2016 and 2017, respectively. GI, SUDS and WSUD have had the most consistent usage over time in the literature.

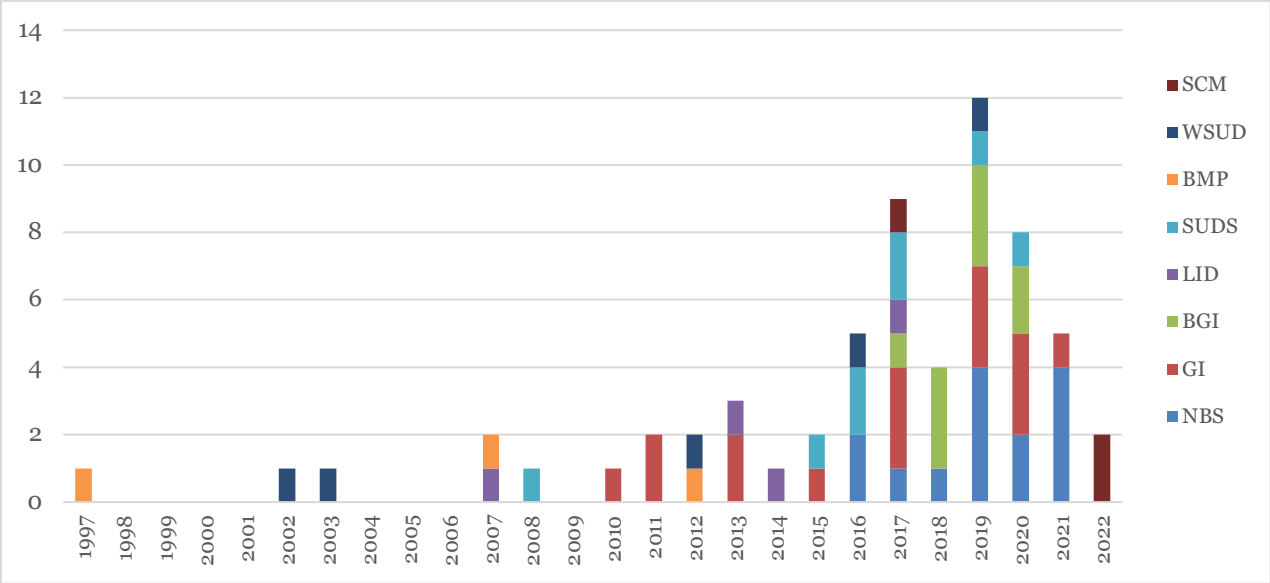

Figure 4-5 Article count by terminology over time

Terminology also varies depending on the region. Figure 4-6 (a-d) shows the terminology breakdown by region. If a study or assessment was carried out in a particular country or region, that is the basis for the regional classification. For studies such as literature reviews that do not focus on a single country or region, the region the authors are based in.

As the figure shows, the Americas have the most variation in terminology, while Australia has the least. NBS is used the most frequently in Europe, and GI is most frequent in North America, with Asia close behind. Some terms are specific to a single country, such as WSUD (Australia), SUDS (UK), and SC (China). BMP and LID were developed and used primarily in the USA and have become less widespread as other terms become more popular.

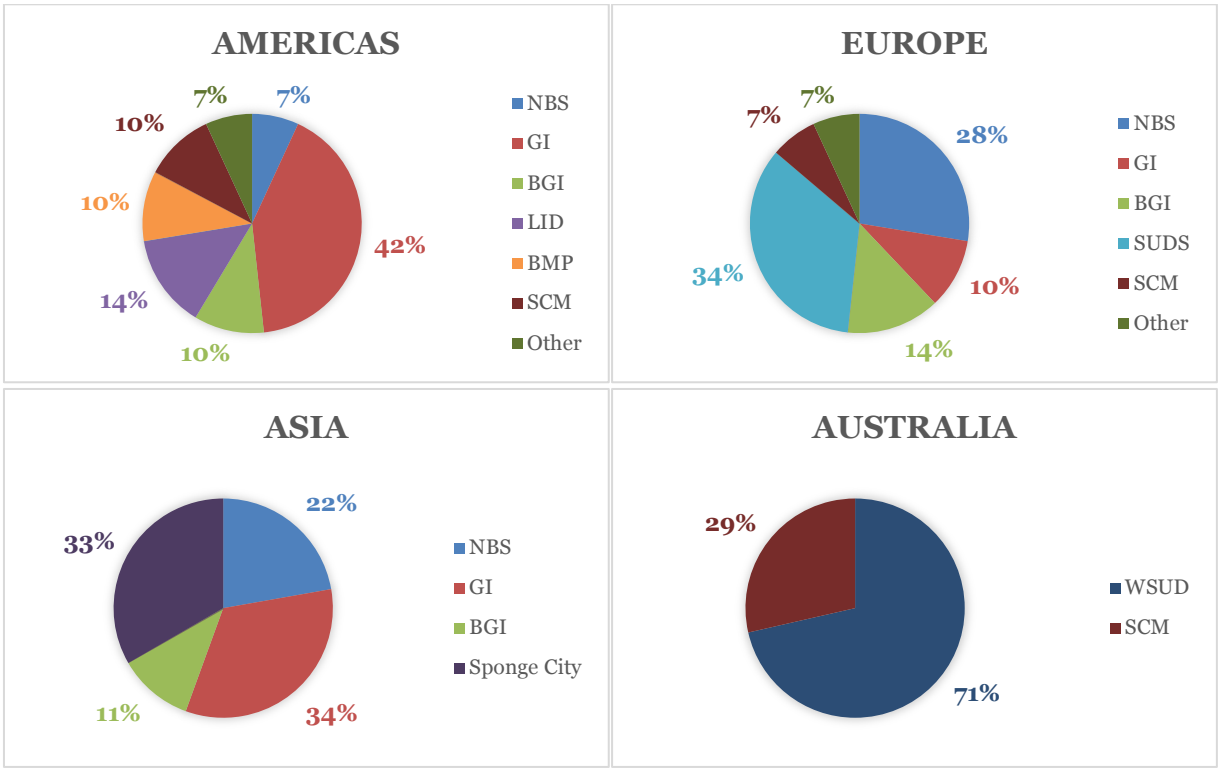

Figure 4-6 a-d Breakdown of terminology by region

While all the terminology used in the literature describe similar concepts, there are some differences among their definitions. One way to categorize the spread of terminology is on a spectrum: on one side, the primary focus is on sustainability, and on the other, the focus is on stormwater management. For example, NBS, as previously mentioned, is a concept that covers many purposes, but can be applied to stormwater. On the other hand, SCM refers to a specific stormwater management process or theory but can be – and often is – made to be sustainable. Depending on the primary function of these measures, different literature is available. When one searches for information on urban drainage, flood, or stormwater management, certain concepts are more likely to come up. When one searches for urban sustainability, urban greening, green spaces, or ecosystems, other concepts are the easiest to discover. In order to illustrate this spectrum, a conceptual model is included in **Error! Reference source not found.**. However, the delineation of concepts by primary function in this way is not concrete, simply a vague comparison, which is why a conceptual illustration can be useful. Another way to categorize the terms is by scale: some terms refer to a single measure used on a single site (SCM, BMP), while others are more general, covering more of the system (SUDS, NBS), and others can be applied either way (WSUD, LID, GI). However, these definitions are not consistent in the literature. Several articles discuss these differences in definitions and concepts: (Matsler et al., 2021, Huang et al., 2020, Fletcher et al., 2015).

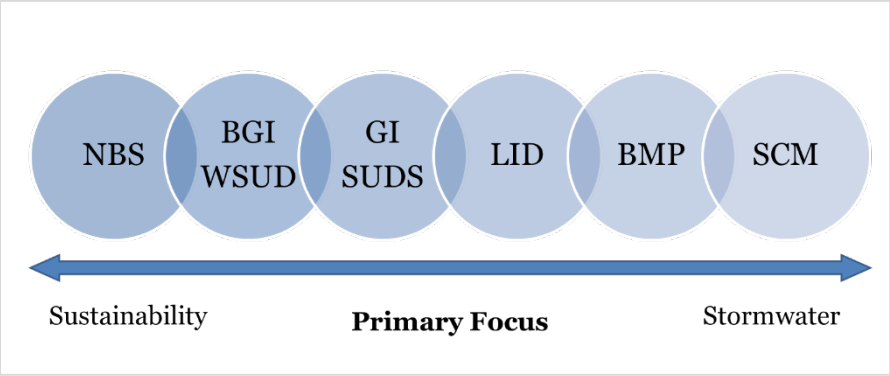

Figure 4-7 Spectrum of terminology by primary focus

4.2 Barriers and challenges for maintenance

21 texts in the literature investigate the barriers and challenges to the implementation of sustainable stormwater management. 8 texts focus on maintenance issues and uncertainty. Using these, a list of challenges and barriers to maintenance has been formulated.

Table 3 Main identified barriers to maintenance of NBS

Barrier	**References**
Highly context specific	DelGrosso et al., 2019, Hammitt, 2010, Flynn et al., 2012, Lashford et al., 2019, Qiao et al., 2018 Moin et al., 2022, Green et al., 2021, World Bank, 2017
Management responsibilities	Sharma et al., 2012, Hammitt, 2010, Kabisch et al., 2016, Sharma et al., 2016, Dhakal & Chevalier, 2017, Blecken et al., 2017, Melville-Shreeve et al., 2018, Qiao et al., 2018, Wihlborg et al., 2019, Cotterill & Bracken, 2020, Wamsler et al., 2020, Månsson & Persson, 2020
Perceptions of sites & site maintenance	Everett et al., 2018, Blecken et al., 2017, Williams et al., 2019, Woods Ballard et al., 2015, Gibbons, 2016, Ferreira et al., 2020, Cotterill & Bracken, 2020
Uncertainty of costs & performance	Li et al., 2020, Macmullan, 2007, Naumann et al., 2011, Ashley et al., 2018, Flynn et al., 2012, Kabisch et al., 2016, Sharma et al., 2016, Davis & Naumann, 2017, Melville-Shreeve et al., 2018, Qiao et al., 2018, Sarabi et al., 2019, Aerts, 2018, Wamsler et al., 2020, Brillinger et al., 2021
Lack of policy drivers/incentives	Davis & Naumann, 2017, Dhakal & Chevalier, 2017, Melville-Shreeve et al., 2018, Qiao et al., 2018, Hoang & Fenner, 2016, Sarabi et al., 2019, Wihlborg et al., 2019, Wamsler et al., 2020, Rahman & Weber, 2003

4.2.1 Importance of local context

In order to best incorporate the natural ecosystem and water cycle, NBS requires knowledge of local climate and ecology (World Bank, 2017). As vegetative cover is often a major part of the system, choosing species that will flourish under local conditions, require minimal maintenance, and that won't introduce invasive species is important (Hammitt, 2010). This knowledge is not only required during the design and planning stages, but also during operation. Maintenance crews also need to understand the ecology of the system, since effective maintenance has a major impact on long-term performance of NBS (Wright et al., 2022). The sort of maintenance necessary to keep sedimentation practices function, for example, are inappropriate for bioretention cells, and decrease efficacy at pollution removal. However, the conditions that can lead to reductions in performance can be difficult for maintenance crews to detect, and often are unnoticed until there are impacts to performance (Green et al., 2021). An understanding of design parameters is necessary for appropriate maintenance for performance (Moin et al., 2022). For example, drawdown rates of bioretention cells need to be high enough to ensure storm event volumes can be processed, but not so high that they prevent pollution removal – the case study in Moin et al. (2022) found that these types of issues that impact water quality are harder for maintenance crews to detect and appropriately manage.

4.2.2 Management responsibilities

A common barrier mentioned in the literature is management responsibilities for operations and maintenance. This especially becomes a challenge when private land is involved in the NBS implementation. While local authorities often play a leading role, planning and management is decentralized and requires several departments to collaborate, in addition to the variety of external actors involved (Qiao et al., 2018). The potential for fragmentation and silo-ing can lead to gaps in planning, and often maintenance is not incorporated into the planning process early enough (Blecken et al., 2017, Shaver et al., 2007). Collaboration with operation and maintenance stakeholders throughout the process is essential to minimalize unforeseen issues and the related costs, such as ensuring adequate access to sites for maintenance (Blecken et al., 2017, Woods Ballard et al., 2015).

When private land is involved in NBS systems, there becomes a question of who assumes responsibility for the system. As was discovered in the case study in Malmö, Sweden, where issues arose between the local authorities, the contractors responsible for maintenance, and private land and business owners where NBS was included, regarding who would assume responsibility for funding maintenance (Månsson & Persson, 2020). Similarly, there is debate surrounding responsibility for the adoption of SUDS in the UK, as mentioned by Cotterill & Bracken (2020), and Melville-Shreeve et al. (2017) discuss.

4.2.3 Perceptions of sites and site maintenance

There are many perspectives of maintenance of NBS within the literature. Some view it as substantial, and more intensive than in conventional systems (Houle et al., 2013), while others believe NBS should be largely self-sustaining and can be left alone (Blecken et al., 2017). This uncertainty in maintenance demands is discussed further in the following section. However, perceptions of maintenance among stakeholders is just one aspect – public perceptions also play a role.

The visible nature of NBS to local residents means aesthetics of the system can be important. Public support and involvement can be affected by negative perceptions of operational NBS. Among several studies in the literature that focus on interviews with residents, many view NBS components to be untidy, often due to neglect and a lack of maintenance (Everett et al., 2018, Williams et al., 2019). However, a lack of education and understanding of the performance of NBS can result in adequate maintenance for design parameters while still seeming untidy to residents, such as less frequent mowing or the attraction of bugs or pests (Woods Ballard et al., 2015). In these cases, compromise might need to be reached to retain public support of the use of NBS.

4.2.4 Uncertainties in costs, lifespan, and performance

It is difficult to find concrete cost estimates for the implementation, operation, and maintenance of NBS, for several reasons. The uncertainty surrounding lifespan leads to uncertainty of long-term maintenance needs and the related costs (Macmullan, 2007). The aging of the system may also play a role in the amount and frequency of maintenance required (Aerts, 2018). The surface-level nature of NBS also means that there is inflow from upstream, and these external flows introduce further uncertainty in performance, especially during storm events (Haghighatafshar et al., 2018). In addition, many of the benefits of NBS, co-benefits to biodiversity, human health, and others are difficult to assign value, which makes cost-benefit analyses difficult (Li et al., 2020, Naumann et al., 2011).

NBS are designed for adaptability and flexibility – this results in inherent uncertainties. Future interactions with the external environment are hard to predict, and will likely impact performance (Ashley et al., 2018). Without established monitoring and reporting systems for gathering performance data, it is difficult to reduce these uncertainties (Esmail & Suleiman, 2020).

4.2.5 Policy framework, incentives

Incentives for private investment and implementation of NBS are currently lacking, and is often cited as a barrier (Davis & Naumann, 2017, Sarabi et al., 2019, Dhakal & Chevalier, 2017). Since local authorities are driving the incorporation of NBS in planning, there is little involvement by industry in promoting sustainable stormwater management (Esmail & Suleiman, 2020). Without economic frameworks that support the investment and innovation by businesses, they are unlikely to accept the financial burden and risk associated with investing in NBS (Davis & Naumann, 2017). In addition, incentives for landowners to incorporate NBS on their property are few and far between. Some cities have attempted to establish such incentives programs, such as providing credits on taxes or utility fees for sustainable measures on a property (Nashville, New York City, Philadelphia, Portland, Seattle, and Washington D.C.), or providing help with start-up costs and guidance on implementation (Chicago, Milwaukee, Nashville, New York City, Philadelphia, Portland, Seattle, Syracuse, and Washington D.C.), mainly for rain barrels, rain gardens, or green roofs (Garrison & Hobbs, 2011). Unfortunately, several of the cities with tax credit programs find that the savings aren't enough to persuade many private properties or businesses to participate.

4.3 Maintenance requirements for sustainable and conventional systems

It is important to investigate sustainable systems by considering a comparison to conventional systems, especially when the purpose is to understand the transition from one to the other. Indeed, much of the perceptions surrounding sustainable systems is in relation to conventional measures, although it is inconsistent. First, perceptions of maintenance will be discussed, followed by details of costs and activities from both case studies and guidance documents.

4.3.1 Perception of maintenance costs and efforts

Several texts in the literature offer the perceptions surrounding maintenance (Moin et al., 2022, EPA, 2013). Perceptions of maintenance demands, including frequency of activities as well as costs, is a frequent discussion point in academic texts when comparing sustainable and conventional systems (Aerts, 2018, Macmullan, 2007, Houle et al., 2013). While some texts discuss the perceptions of maintenance demands to be mistakenly higher than in reality (Houle et al., 2013, Somarakis et al., 2019), an equal number discuss mistaken perceptions as lower, minimal, or even self-maintaining (Blecken et al., 2017, Månsson & Persson, 2020).

According to Houle et al. (2013), there is a perception of substantial maintenance requirements of LID by the public, developers, and decision-makers, while advocates consider the maintenance requirements to be

lower. Somarakis et al. (2019) agrees, stating that costs for NBS, including maintenance, are often perceived as higher than grey solutions. In additional studies of Toronto, Canada (Johns, 2019), USA (Fitzgerald & Laufer, 2017, Thorne et al., 2018), Malmö and Helsingborg, Sweden (Wihlborg et al., 2019), Semarang, Indonesia (Drosou et al., 2019), Southern Australia (Kabisch et al., 2016), South Korea (Han & Kuhlicke, 2021), and the UK (Melville-Shreeve et al., 2018), interviews with municipal officials, consultants, developers, and community actors highlight their uncertainty in maintenance costs, and fears of higher costs and lower performance when comparing with traditional systems.

However, as Blecken et al. (2017) point out,

> "there is an expectation [by managers of stormwater systems] that once constructed, SCMs will function well without any oversight"(Blecken et al., 2017, 278).

This is corroborated by Månsson and Persson (2020) in their review of a sustainable stormwater project in Malmö, Sweden, reflecting that the managers had an image that the system would largely take care of itself.

When looking at several guidance manuals outlining the design, operation, and maintenance considerations of NBS, such from the US Environmental Protection Agency (EPA), Department of Transportation (DOT), and the Army Corps of Engineers (ACE), the IUCN, and the European Union's Horizons 2020 research programme (ThinkNature), there are further contradictions regarding costs and demands of maintenance.

In a report assessing several green infrastructure projects, the US EPA discusses maintenance demands:

> "…green infrastructure can have more intensive maintenance demands due to the need for greater frequency and subsequent additional labor hours necessary for optimal performance" (US EPA, 2013, 7),
>
> "generally a less costly alternative than gray infrastructure due to savings in installation, cost of maintenance activities, and greater adaptability of the infrastructure" (US EPA, 2013, 7),
>
> "may not always be less expensive to construct or maintain" (US EPA, 2013, 8), and
>
> "some require less maintenance than their grey counterparts, while many require more" (US EPA, 2013, 8).

Similarly, in the ThinkNature Handbook:

> "There is… a misunderstanding concerning the cost of the techniques for NBS (including maintenance), as this is often mistakenly perceived to be higher than grey solutions" (Somarakis et al., 2019, 93),
>
> "Although the maintenance costs of NBS are often lower than their grey infrastructure alternatives, in practice it is often perceived to be even lower than it actually is, and several NBS schemes fall into disrepair or sub-optimal functioning" (Somarakis et al., 2019, 131).

From the US DOT, regarding costs:

> "Routine maintenance costs for well-designed and well-built nature-based solutions should be minimal but are unlikely to be zero. It is unfair to generally state that the maintenance costs of

> nature-based solutions are less than those of traditional approaches. Maintenance costs and maintenance intervals vary by approach" (Webb et al., 2019, 158-159).

A common perspective in these guidance manuals is the idea that natural systems are capable of self-maintaining, a perception pointed out by Blecken et al. (2017) above. From the US ACE:

> "An advantage of well-designed [NBS] is the ability to "self-maintain" using natural processes… which can significantly reduce long-term maintenance costs and the need for infrastructure upgrades" (Bridges et al., 2021, 237).

Additional to this idea of "self-maintaining" systems is "self-sustaining" which may sound similar but has some key differences. From the IUCN:

> "If NBS interventions are implemented correctly, they have the capacity to self-sustain over time" (Cohen-Shacham et al., 2016, 30).

And the US DOT:

> "Successful nature-based solutions will be more self-sustaining over the long term, since the shared goal of all nature-based solutions is to restore and/or provide natural ecosystem functions" (Webb et al., 2019, 160).

However, in the context of these documents, self-sustaining doesn't refer to maintaining function or performance without any maintenance interventions, but rather is about adaptive capacity (Webb et al., 2019). NBS, especially ones that limit the inclusion of built infrastructure, do not depreciate in value over time the way grey infrastructure does, due to wear and tear on the concrete or other manufactured components (Cohen-Shacham et al., 2016).

In all, the discussion surrounding maintenance demands and costs, when not citing specific numbers for a case study, highlights many conflicting perspectives.

4.3.2 Maintenance costs

Despite the conflicting ideas about maintenance costs and demands shown in the previous section, there is data supporting the conclusion that maintenance requirements decrease over time. While initial maintenance requirements can be higher during what is called the 'establishment period' – time for vegetation to grow to optimal levels, with more frequent inspections and routine gardening actions, generally lasting one to three years – over time those maintenance needs decrease (Woods Ballard et al., 2015). This is corroborated with studies done by Lloyd et al. (2002), Garrison & Hobbs (2011), and Houle et al. (2013), which show that overall, costs go down over time (Figure 4-8 and Figure 4-9). In Garrison & Hobbs (2011), the case study of New York City highlights the results of an investigation done by the city which indicates that GI projects are more cost-effective in the long-term than equivalent grey infrastructure projects, and consequently promoting implementation of GI in the NYC Green Infrastructure Plan in 2010.

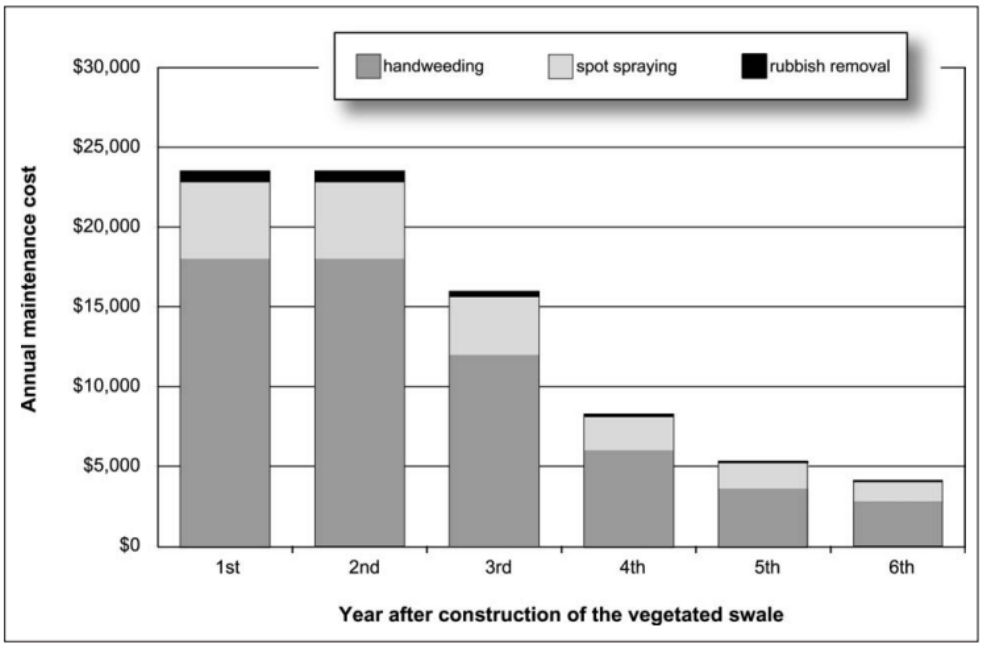

Figure 4-8 Investigation into maintenance costs by Indigenous Gardens Pty Ltd. (2002), showing a decrease over time. Source: Lloyd et al., 2002

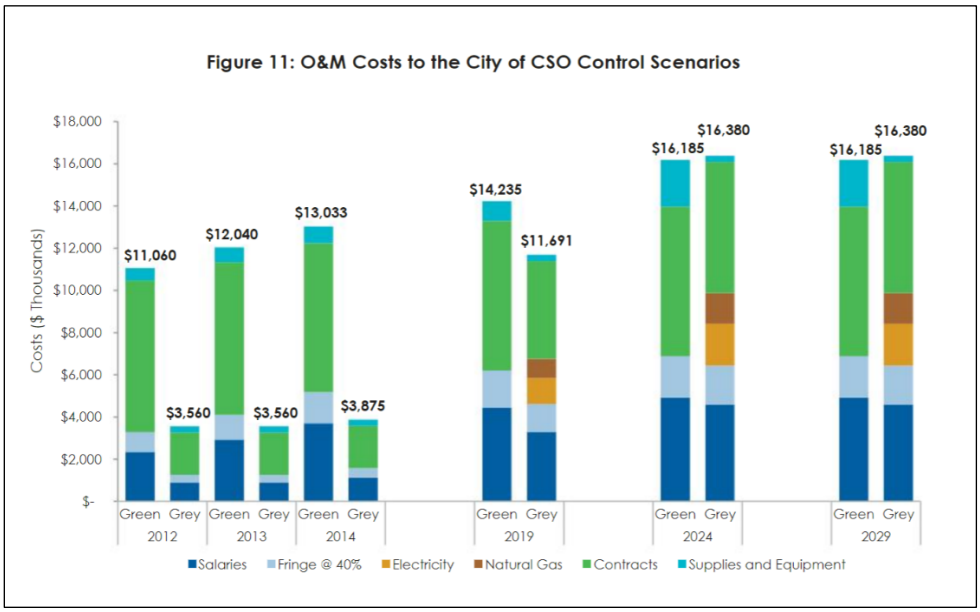

Figure 4-9 Operation and maintenance (O&M) cost estimates by the City of New York, showing the comparison between green and grey options. Source: NYC Green Infrastructure Plan (2010)

Duffy et al. (2008) show that life-time costs of natural solutions maintenance are lower on average, in their study comparing SUDS to conventional measures, but point out that natural systems maintenance rely on economies of scale – larger, more centralised systems incur lower costs than smaller, spread-out systems – which is corroborated by Blecken et al. (2017).

However, several studies have also shown that life-time costs for natural systems can end up higher than conventional ones, such as Månsson & Persson (2020), due to a lack of prior knowledge of how the system

would work and therefore more costs were incurred after implementation as issues and challenges came up. Other case studies show similar lessons learned for costs and the importance of expertise surrounding maintenance and including it early in the planning process (Moin et al., 2017, Fitzgerald & Laufer, 2017).

Due to the multi-functional nature of sustainable systems, cost-benefit analyses must also take into account co-benefits, as the study by Alves et al. (2020) and the literature review by MacMullan (2007) show. Many social, environmental, and economic benefits are not associated with the primary function of NBS, but their inclusion in a cost-benefit analysis can significantly affect the economic analysis and therefore decision-making (Alves et al., 2020). However, co-benefits are often difficult to quantify in terms of value (Davis & Naumann, 2017). Table 4 is adapted from Davis & Naumann (2017), illustrating many of these co-benefits and the way NBS can contribute.

Table 4 Examples of co-benefits.

Benefit	**Description**
Air quality improvement and reduction of impacts to human health	Air particulate filtering via vegetation (e.g., trees and green roofs)
Air and building temperature	Cooling or insulation; thermal comfort and energy savings
Biodiversity and ecological value	Habitat creation and enhancement, connecting habitats
Carbon reduction and sequestration	Low energy needs (materials, construction and maintenance), lower water use, sequestration (e.g., trees and wetlands)
Economic growth	Business, jobs, productivity, tourism, property prices
Education opportunities	Community engagement (before and after construction), information boards, education programmes
Groundwater and soil moisture recharge	Improved water availability or quantity through interception, infiltration, and runoff treatment
Health and well-being	Air quality improvement, air temperature reduction, reduced flood risks
Recreation	Involvement in specific recreational activities
Security of water supply	Rainwater harvesting; improved water availability and quantity
Reduced flows and volume to treat in combined sewer systems	Interception and further runoff volume reduction
Visual character	Attractiveness and desirability of area
Surface water quality improvements	Pollution prevention strategies, interception, runoff treatment

Reference: Davis & Naumann (2017)

Funding for sustainable systems also comes into play, as a commonly mentioned barrier to incorporation of NBS – studies in Indonesia, Canada, USA, and UK all include discussions of funding. While some places, like the US, have programs for grants and funding of NBS, many places do not, and without them,

sustainability in urban flood management is considered a luxury (Drosou et al., 2019). Funding structures are discussed further in Section 4.4.

4.3.3 Maintenance activities

Most maintenance activities for sustainable systems fall under what can be called 'site maintenance' – weeding, removal of litter and debris, mowing, cleaning out gutters, trimming roots (Gibbons, 2016). Some system maintenance is also necessary, such as cleaning tanks, geotextiles, and filters, clearing blockages from pipes, and repairing erosion damage, depending on the type of sustainable measure implemented. Guidance from CIRIA (Woods Ballard et al., 2015), the Watershed Management Institute (Livingston et al., 1997), the US DOT (Webb et al., 2019), and the North Inlet-Winyah Bay National Estuarine Research Reserves (Ellis et al., 2014), and texts by Flynn et al. (2012) and Erickson et al. (2013) offer specific maintenance tasks, inspections, and frequencies for a variety of sustainable measures. Inspections are the first measure taken, to ensure continued performance. In the event that inspections discover issues, maintenance actions can be taken. Table 5 below covers the most common activities.

Table 5 Common maintenance activities for NBS

NBS practice	**Maintenance activities**
Sedimentation	Routine actions: • Removal of litter & debris • Cutting grass, removing weeds, pruning trees, managing vegetation Occasional or remedial actions: • Reseeding areas as needed, after storm events or other unusual conditions • Repairing erosion damage • Realigning riprap • Re-levelling uneven surfaces • Dredging to remove sediment build-up • Aerating ponds if eutrophication is significant
Filtration	Routine actions: • Removal of litter & debris • Cutting grass, removing weeds, pruning trees, managing vegetation • Cleaning and removing build-up of geotextile or filter Occasional or remedial actions: • Reseeding areas as needed, after storm events or other unusual conditions • Repairing erosion damage • Realigning riprap • Re-levelling uneven surfaces • Removal or control of tree roots • Re-levelling uneven surfaces • Replacement of geotextile or filter • Cleaning of sediment clogging inlets/pipes

Infiltration	Routine actions: • Removal of litter & debris • Cutting grass, removing weeds, pruning trees, managing vegetation • Cleaning gutters • Cleaning and removing build-up of geotextile or filter • Brushing and vacuuming of surfaces (permeable pavement) Occasional or remedial actions: • Clearing sediment deposits • Reseeding areas as needed, after storm events or other unusual conditions • Repairing erosion damage • Realigning riprap • Re-levelling uneven surfaces • Replacing of geotextile or filter • Repairing cracks, depressions, rutting, and misalignment (permeable pavement)
Bioretention	Routine actions: • Removal of litter & debris • Assessing vegetation for disease, infection, or poor growth • Cutting grass, removing weeds, pruning trees, managing vegetation • Maintaining plant density • Mulching and replacing top layer of soil Occasional or remedial actions: • Fixing holes in filter media • maintaining erosion protection • removal of invasive species • Repairing erosion damage • Repairing of cracked or disturbed inlets

References: Woods Ballard et al., 2015, Moin et al., 2022, Erickson et al., 2013, Ellis et al., 2014, Guo, 2017

The maintenance of conventional systems is discussed by the US Bureau of Reclamation, the American Society of Civil Engineers (ASCE, 2006), and Fontecha et al. (2016). While site maintenance is still included, the degree is much lower, and mainly implemented around inlets and outlets of the pipe systems. More important is monitoring for pipe failures due to shifting of pipe alignment and grade, collapses, pulled joints, and blockages (US Bureau of Reclamation, 1993). Due to the underground nature of most conventional system components, monitoring becomes much more important, as visual inspections are difficult to make (Fontecha et al., 2016). As well, the mechanical and electrical components require regular maintenance in order to prevent failures (ASCE, 2006). Without vegetated components, conventional system maintenance includes pollutant removal that NBS doesn't require (Mullaly, 2019).

Table 6 summarizes the activities below. Similar to NBS, more frequent inspections should be undertaken in the first few years following implementation to ensure design performance (US Bureau of Reclamation, 1993).

Table 6 Common maintenance activities for conventional systems

Conventional system component	**Maintenance activities**
Pipelines & storage basins	Routine actions: • Inspecting along surface above pipelines for sinkholes, wet spots, and tree growth Occasional or remedial actions: • Repairing of shifted pipe alignment or grade, collapsed pipe sections, pulled joints • Flushing or mechanical clearing of clogging due to sediment • Cleaning to remove accumulated pollutants • If no manhole access is convenient, excavation downstream, removing of joints to allow access of cleaning equipment • Backfilling small sinkholes • Replacement of broken pipes, repair of pulled joints with additional pieces of pipe to retain connections
Inlets/outlets/manholes	Routine actions: • Removal of litter & debris • Cleaning of screens to remove moss & algae growth • Cutting grass, removing weeds Occasional or remedial actions: • Removal of trees & shrubs, including roots • Dredging to remove sediment build-up • Repairing erosion damage • Reseeding areas as needed, after storm events or other unusual conditions • Spoil banks re-seeding & fertilizing after dredging to stabilize excavated material
Electrical & mechanical components	Routine actions: • Following maintenance guidelines from manufacturer for pumps and motors • Lubrication or packing adjusting of mechanical equipment Occasional or remedial actions: • Shutting down of electrical system and contact manufacturer for repair instructions • Replacement of worn or outdated electrical components

	• Removal & repair or replacement of appurtenances such as valves, covers, flap gates, or trash racks, ensuring continued operation while the appurtenance is removed

References: ASCE, 2006, US Bureau of Reclamation, 1993, Mullaly, 2019

4.4 Policy and governance instruments

Many of the discussion on barriers in the literature either mention or focus on policy and governance instruments that affect the transition to more sustainable urban stormwater management. In the literature, the most commonly cited barriers in current policy and governance are related to institutional inertia and a bias towards conventional systems. Funding is the next major barrier mentioned.

The instruments that can aid the transition to sustainable stormwater management are designed to provide the knowledge and data needed to reduce the long-term uncertainties surrounding NBS.

4.4.1 Bias of establishment and institutional inertia

Historically, management of conventional systems is centralized & technocratic – typically covered by a single (or very few) governmental departments, with established design standards and codes, including at the national level (Dhakal & Chevalier, 2017). The system itself is also one large, connected network of gutters, pipes, storage tanks, and outlet structures. In contrast, NBS is characterized by a system, or "treatment train" of interventions, many of which are small-scale, at a single site (Shaver et al., 2007). Consequently, the management of NBS is also decentralized – many governmental departments, along with more stakeholders, are involved. Fragmentation of governance is therefore a challenge in the management of NBS; one of the most commonly discussed in the literature (Esmail & Suleiman, 2020, Keeley et al., 2013, Dhakal & Chevalier, 2017). The expertise necessary for NBS, as previously discussed, differs from that of conventional systems, resulting in knowledge gaps by those involved in development and management, and several collaborating departments will inevitably have competing interests (Fitzgerald & Laufer, 2017).

Dhakal & Chevalier (2017) investigates the specific federal, state, and municipal policies that impact NBS in the United States. The findings indicate an entrenched "pro-grey" bias, which is corroborated by Johns (2019), similarly investigating Canada. For example, federal law in many countries traditionally considers stormwater runoff a nuisance, rather than a resource, which enables landowners to protect their land from runoff by any means necessary, without regard for neighbours or the hydrologic cycle (Dhakal & Chevalier, 2017). Other regulatory restraints include mandatory connections to piped drainage systems (Qiao et al., 2018). Unlike conventional systems, design and maintenance standards and codes for NBS do not yet exist, or are not well established in regulatory frameworks, and there are few legislative mandates encouraging their implementation (ibid.).

4.4.2 Funding and costs

Lack of funding is posed as a major barrier to effective transition to NBS by much of the literature (Johns, 2019, Thorne et al., 2018, Drosou et al., 2019, Keeley et al., 2013). Funding for NBS can be difficult to obtain for many municipalities that are open to it, despite the proven cost-effectiveness, and the variety of benefits NBS can provide over grey infrastructure. Traditionally, stormwater management is funded through general revenue, and these public funds have legal restrictions from being implemented on private property – a complication when NBS often requires private land (Dhakal & Chevalier, 2017). In the study by Keeley et al. (2013) of Cleveland and Milwaukee in the United States, several other impacts to funding are pointed out: few, if any state and federal grants are available and difficulties in raising utilities and taxes due to a

lack of public support and an "anti-tax" culture. In addition, as Sharma et al. (2016) points out, many financial schemes and grants are one-off, capital cost payments, without consideration for the long-term operation and maintenance needs. The US EPA corroborates this in their report on operations and maintenance of green infrastructure (EPA, 2013). Contributing to this is the perception of NBS as short-term or temporary solutions, which conflicts with the reality of NBS as requiring long-term management and often having a return on investment of more than a decade (Kabisch et al., 2016, Dhakal & Chevalier, 2017). Another concern regarding funding is the uncertainty surrounding long-term maintenance costs and lifespan of the system. Even when municipalities are interested in incorporating or have been incorporating NBS, the oldest systems are still only around twenty years old, so the performance changes and end-of-life stages of these systems are still relatively unknown. Lasting political support and funding is therefore not guaranteed, when one cannot concretely say how long it will be necessary (Thorne et al., 2018).

When municipal budgets don't have space for funding projects, other sources of revenue are considered for the continuous operation and upkeep of systems. In many cities a stormwater fee has been implemented, such as Philadelphia (Fitzgerald & Laufer, 2017), that operates not on water usage, but on impervious cover and contribution to runoff. The collection of case studies in Garrison & Hobbs (2011) highlight several other American cities that have made a similar transition. However, in several studies of residents' views on stormwater management, it is commonly viewed as the municipality's responsibility, and there can be push-back when residents feel they suddenly have to pay for such services, such as in the studies in Canada, the UK, and the United States discuss (Drescher & Sinasac, 2021, Williams et al., 2019, Keeley et al., 2013).

Another avenue for funding is private investment, which has its own issues for NBS. Many of the co-benefits that NBS provide, such as ecosystem services, biodiversity, and social benefits are difficult to quantify for effective cost-benefit analyses, and therefore don't have a clear market for investment from industry (Esmail & Suleiman, 2020). Studies such as the ones by Alves et al. (2020) highlight the need for more clear inclusion of these co-benefits in cost-benefit analyses, to better represent NBS as a viable alternative to conventional stormwater systems.

4.4.3 Methods and instruments for transition

While the technical expertise needed for NBS implementation is becoming more easily accessed, in many regions and countries there remains a lack of practical experience at the local level (Sharma et al., 2012). The transition to a new generation of planners and engineers brings new knowledge & experience, as sustainable systems have more recently been incorporated into education (Wihlborg et al., 2019). Monitoring and reporting systems will be a major factor in understanding long-term function, efficacy, and maintenance requirements of sustainable systems (Esmail & Suleiman, 2020, Green et al., 2021). Developing maintenance guidelines and best practices at the local level takes practice – the more NBS is implemented and operated, the more knowledge will come from monitoring. This is exemplified in Philadelphia, which utilizes double-loop learning to establish their own design and maintenance manual for NBS (Fitzgerald & Laufer, 2017). Brisbane, Australia offers another example. Several projects incorporating WSUD principles have been used to establish design tools and standard drawings, in order to reduce cost and maintenance uncertainties in future development, such as road design projects that were used as precedent for incorporating WSUD in standard road corridors (Rahman & Weber, 2003).

Wamsler et al. (2020) discusses several policy and governance strategies for mainstreaming of NBS for climate change adaptation in Sweden. While the focus of that study is on implementation, several can be adapted to maintenance strategies. In particular, targeted and strategic stakeholder and public participation in the maintenance planning process. Involving landowners, site managers, maintenance crews, and experts (either in industry or academia) can contribute to reducing the risks and uncertainties surrounding maintenance and creating regulatory and planning frameworks (Wamsler et al., 2020).

The mainstreaming of tools such as hydrologic modelling, scenario modelling, and cost-benefit analyses also help with more widespread adoption of NBS (Esmail & Suleiman, 2020). As previously mentioned, knowing what components of NBS best fit a local context can be difficult, so these tools can provide the data that is necessary to make those decisions. Some of these tools are showcased in the literature: the BEST tool for comparing benefits (Ashley et al., 2018), optimization of co-benefits (Alves et al., 2020), cost benefit analyses using life-cycle assessments (Vineyard et al., 2015), and hydrologic modelling at the watershed scale (Chen et al., 2019, Brauman et al., 2022).

5 Discussion

The results of the data analysis reported in the previous section will be used to tackle the three research objectives of this study. By understanding the terminology, concept, and definition issues, the major barriers the maintenance, the differences in maintenance between sustainable and conventional systems, and the policy and governance framework surrounding maintenance, the research objectives can now be investigated.

The following sections address the research objectives:

1) *Comparison of green and grey* maintenance approaches and how they are perceived, understood, and planned in respect to urban flood management, and

2) *Barriers, challenges, risks, and opportunities* relating to maintenance, how they impact the transition to sustainable flood management approaches, and their policy and governance integration.

5.1 Comparing green and grey

5.1.1 Perceptions of maintenance

The issues and contradictions regarding maintenance demands in the guidance documents in this literature review have no doubt contributed to the confusion evident in decision-makers, implementers, and developers of NBS. Clarity here is essential: overestimating maintenance demands and costs leads to reluctance to implement, while underestimating leads to disrepair and costly adjustments after implementation, and often failure.

5.1.2 Incorporation into the planning process

In most of the design manuals in the literature, maintenance is a step covered near the end of the process, without consistent consideration throughout the process. Only the guidance provided by CIRIA includes discussion of maintenance throughout design, specifically by mentioning the importance of access to sites for maintenance activities (Woods Ballard et al., 2015). As Blecken et al. (2017) discusses, incorporating maintenance needs throughout the design process is essential.

In comparison to the assorted NBS design manuals, conventional grey systems design does not explicitly mention maintenance very often outside of an operation and maintenance plan guide. This could be due to the incorporation of maintenance into the design itself – such as ensuring high enough flow rates through pipe systems to prevent settling of sediment and therefore reduce the need for clearing sedimentation build-up during operation. However, maintenance activities, especially inspections, are mentioned within the O&M plan guidance. Because the major components of conventional systems are underground and standardized, maintenance activities are clearly defined.

5.1.3 Above vs below ground measures

Because conventional systems are completely public owned, maintenance crews are either owned or contracted by the utility or municipality, thereby reducing much of the uncertainty surrounding management that NBS must deal with. In addition, the nature of NBS as surface-level measures means routine landscaping or site maintenance has a higher impact on hydrologic performance of the system. While landscaping maintenance is still performed for conventional systems, and in particular is important around inlets and outlets, keeping sites tidy, lawns mowed, and weeds cleared does not have the same effect without filtration or infiltration practices. The addition of runoff from upstream areas, especially ones that do not include NBS, is also a consequence of surface-level measures, as is their visibility to the public.

In particular to sustainable systems, the understanding and analysis of maintenance is highly variable due to the uncertainty and misconceptions evident throughout the literature.

5.2 Barriers, challenges, risks, and opportunities

5.2.1 Terminology and uncertainty

When dealing with such a variety of terminology, it becomes difficult to access a reasonable cross-section of literature available. Even though many of the terms covered in this study have similar or overlapping concepts, it took an expanding list of search terms to find the variety of literature in this review. While initial, more general searches (using the most common terms: NBS and GI) often included mentions of a variety of other terms, using specific search terms was necessary to find texts focusing on specific terminology (WSUD, Sponge Cities). As was discussed in the terminology section of the results, the main eight terms had varying definitions along a spectrum (**Error! Reference source not found.**). Depending on the perspective of the individual (sustainability vs stormwater) searching for literature, different results will be found. This also contributes to the complexity of accessing a comprehensive body of literature, and hence understanding the core concepts.

Uncertainty regarding NBS performance, life span, and costs is frequently cited as a major barrier to implementation (Thorne et al., 2018, Keeley et al., 2013, Sharma et al., 2016, among others). It is clear that despite the several examples in this literature review, including both guidance manuals and academic texts, that discuss those exact parameters, the lack of consistency in terminology and concept definitions plays a role. This inconsistency contributes to the fragmentation of the body of knowledge available to developers and decision-makers at all levels, but especially the local level (Matsler et al., 2021). Indeed, the presence of a design manual from the mid-1990s (Livingston et al., 1997), shows that the theory behind the NBS concept has been around for nearly three decades. Of course, these early examples of literature have less of an emphasis on sustainability, a concept which has gained popularity more recently, and rather simply refer to them as best practices.

This knowledge gap highlights the need for more investigation into maintenance of NBS, as well as more cohesion in literature. The case studies and interviews throughout the literature also emphasize how the uncertainty in long-term costs, maintenance needs, and performance contribute to the perception of NBS as risky and experimental, which often dissuades them from implementation.

5.2.2 Education and knowledge gathering

Public support of NBS often lies in the impact on residents' lives. Untidy and poorly maintained components reflect poorly on the efficacy of NBS. However, the difference in maintenance for aesthetics and performance means what some residents find untidy is simply the optimal conditions for performance. This difference could be better promoted through public engagement and education programs. Including residents in maintenance activities is also mentioned several times as an option for reducing costs and improving public understanding, however many do believe stormwater management to be solely the municipality's responsibility.

The investigation into Philadelphia (Fitzgerald & Laufer, 2017) also highlights the need for learning as you go. The double-loop learning system is an example of how to gain the local, context-specific knowledge necessary for design and operation of NBS. While uncertainties during the design process can lead to costly adjustments, such as the ones highlighted in Månsson & Persson (2020), the review process implemented in Philadelphia provides one way to learn from mistakes and gain the knowledge base required that is often a steep price of admission into the wider uptake of NBS.

5.2.3 Policy and governance

Effective policy integration of NBS faces many challenges. The pro-grey bias in North America, and the prioritizing of other concerns in developing regions like Indonesia both see sustainability as something to worry about later, especially without adequate funding or incentives. In contrast, Sweden in particular is leading the way with incorporation of NBS and climate adaptation into policy.

Some of the tools mentioned in the literature can be used to help minimize the uncertainty surrounding maintenance, performance, lifespan, and costs. Monitoring and reporting programs, while often difficult to implement, are severely lacking where NBS is utilized. Comprehensive monitoring can contribute the kind of empirical evidence of performance, persuading decision-makers to implement (Esmail & Suleiman, 2020). Until there is concrete evidence, NBS will continue to be perceived as risky.

The strategies discussed in the literature, such as the case studies of Philadelphia, Sweden, and Australia, remain isolated and scattered solutions, limited to very few countries. Combating silo thinking in governance frameworks is particularly difficult and establishing management responsibility and stakeholder cooperation necessary for NBS implementation and maintenance is often full of conflict (Davis & Naumann, 2017). If cities are invested in fostering the transition to sustainable systems, new, collaborative, governance structures are needed. In particular, promoting collaboration between experts, both in industry and academia, and local decision-makers and implementers that currently don't have the experience or knowledge to effectively implement and maintain NBS.

6 Conclusions

Due to the pressures from increasing urbanization, climate change, and aging infrastructure, conventional "grey" stormwater management systems are no longer the most effective solution. By transitioning to sustainable stormwater management systems, these pressures can be alleviated, as well as providing benefits to biodiversity, pollution reduction, and human health. While academic interest in nature-based solutions as sustainable stormwater management has been well-documented, the uncertainties and challenges associated with the maintenance of these systems is less well understood. The literature review in this study covered the maintenance requirements of both conventional and sustainable systems, as well as many of the challenges, such as lack of expertise, unclear management responsibilities, perceptions and misconceptions of maintenance, uncertainties in costs and performance, and lack of effective policy and governance integration. The uncertainties surrounding sustainable systems is also due to the complexity of language and terminology used to represent sustainable stormwater management concepts, with a variety of terms used around the world, and with varying definitions.

This report highlights the need for clarity in definitions and terminology, in order for more accessible expertise from academic research. Information sharing and collaboration is also vital to the smooth transition from conventional to sustainable stormwater systems. Education doesn't end with the decision-makers and implementers, it also extends to the public, as support from residents living near NBS components is necessary for integration.

To reduce the uncertainty involving maintenance, such as in long-term costs and lifespan, and therefore the perception of risk, long-term monitoring and reporting programs will be invaluable. The evidence gathered from these programs will contribute to the body of knowledge of NBS and help encourage its widespread uptake.

While there are differences in maintenance planning, demands, and requirements in conventional and sustainable stormwater management, the demands and costs of sustainable systems are not inherently greater, and in many cases can be lower if they are well understood and incorporated throughout the planning process.

7 References

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Appendix A Literature review spreadsheet

Author	Year	Title	Publication/ Publisher	Type of literature	Location	Terminology	Stormwater system components	Topic of Discussion	Content	Source	Search Terms
USBR	1993	Drainage Manual	US Department of the Interior	Grey literature	USA	drainage systems	pipes, culverts, open drains, pump stations	design, implementation, and maintenance guidance	Manual for design, implementation, and maintenance for urban drainage systems	From reference	
Livingston et al	1997	Operation, Maintenance, & Management of Stormwater Management Systems	Watershed Management Institute, Inc.	Grey literature	USA	**BMP,** STP	infiltration basins, pervious pavement, wet & dry ponds, biofiltration, wetlands	Maintenance guidance	manual for operation & maintenance of BMPs	Google scholar	maintenance, stormwater management
Lloyd et al	2002	Water sensitive urban design: a stormwater management perspective.	Cooperative Research Centre for Catchment Hydrology	Industry report	Australia	**WSUD**, BMP, BPP	biofiltration systems, vegetated swales, wetlands	Overview of the WSUD concept, with a case study of the Lynbrook Demonstration Project.	Refines existing knowledge of WSUDS at the lot scale to whole catchments. Focuses on structural stormwater management strategies in terms of life cycles, design process, construction, monitoring, and cost effectiveness regarding maintenance is essential to improve implementation.	Google scholar	water sensitive urban design australia
Rahman & Weber	2003	Sustainable urban development in Brisbane City - the Holy Grail?	Water Science and Technology	Academic article	Australia	**WSUD**	vegetated swales, bioretention systems, rainwater harvesting systems, constructed wetlands	Case study of Brisbane, Australia	Analysis of policy and planning in Brisbane for WSUD. Challenges discussed: external stakeholder resistance, integration with other development issues (road layouts, park requirements)	KTH Library database	WSUD maintenance
ASCE	2006	ASCE Guidelines	Environmental and Water Resource Institute of the American Society of Civil Engineers	Grey literature	USA	Urban stormwater systems	pipes & conduits, drainways, detention & retention facilities, pump stations	design, implementation, and maintenance guidance	Standards and guidelines for design, implementation, and operation and maintenance of urban drainage systems. Covers both conventional and sustainable measures without distinction.	ASCE library	drainage, maintenance

Author	Year	Title	Publication/ Publisher	Type of literature	Location	Terminology	Stormwater system components	Topic of Discussion	Content	Source	Search Terms
MacMullan	2007	The Economics of Low-Impact Development: A Literature Review	ECONNorthwest	Academic article	USA	**LID**	bioswales, rain gardens, pervious pavement,	Cost-effectiveness, comparison to conventional systems, barriers to sustainable systems.	literature review focusing on economic aspects, cost-benefit analysis, and comparison with conventional measures. Challenges discussed: most of the side benefits LID provide cannot be easily quantified for a cost-benefit analysis, O&M costs are not easily understood & quantified	From reference	
Shaver et al	2007	Fundamentals of Urban Runoff Management: Technical and Institutional Issues (2nd edition)	North American Lake Management Society	Grey literature	USA	**BMP**, LID, WSUD, SUDS	bioretention systems, rain gardens, rainwater harvesting, retention pond, pervious paving, vegetative filter, wetland	design, implementation, and maintenance guidance.	manual for runoff management considerations, includes operations & maintenance section with regulatory discussion	From reference	
Duffy et al	2008	A cost comparison of traditional drainage and SUDS in Scotland	Water Science & Technology	Academic article	UK	**SUDS**	retention ponds, constructed wetland	Comparison of sustainable and conventional systems	comparison of SUDS and a hypothetical grey infrastructure system. Comparison covers costs of implementation and maintenance, with activities and frequencies. Finds overall maintenance costs to be lower, but highlights relevance of economies of scale	From reference	
Hammit	2010	Toward Sustainable Stormwater Management: Overcoming Barriers to Green Infrastructure	M.I.T.	Academic article	USA	**GI**, GSI, LID	rain gardens, green roofs, permeable pavement, rainwater harvesting, vegetated swales, wet ponds	barriers to sustainable systems, with interviews (municipal officials, urban planners) and case studies.	barriers discussed: lack of ecology/ biology/ gardening knowledge in maintenance work, lack of applicability in current design & maintenance techniques, ambiguity in responsibility, site suitability & conditions, risk aversion	From reference	

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Naumann et al	2011	Design, implementation, and cost elements of Green Infrastructure projects	European Commission	Industry report	EU	**GI**	general	Barriers and drivers to sustainable systems, cost-benefit analysis	Reviews terminology and typology, cot-effectiveness, and cost-benefit analyses for GI. Barriers discussed: lack of clarity of management responsibilities, public/private land, lack of funding & regulatory framework, lack of expertise, knowledge gaps, cultural barriers	Google scholar	green vs grey infrastructure costs
Garrison & Hobbs	2011	Rooftops to Rivers II: Green strategies for controlling stormwater and combined sewer overflows	Natural Resource Defense Council	Industry report	USA	**GI**, BMP, LID	green roofs, vegetated swales, rainwater harvesting, infiltration basins, filter strips, permeable pavement	Case studies of American cities	Using the Emerald City rating system, analyses eight American cities for their incorporation of GI in urban stormwater management, looking at funding, regulatory frameworks, incentives	From reference	
Sharma et al	2012	Impediments and constraints in the uptake of water sensitive urban design measures in greenfield and infill developments	Water Science and Technology	Academic article	Australia	**WSUD**, IUWM,	rainwater harvesting systems, detention ponds, bioswales, biofiltration systems, permeable pavement, green roofs, wetlands	Barriers to sustainable systems, social & institutional focus	barriers discussed: fragmentation of policies, lack of acceptance across stakeholders, community perceptions, institutional inertia, uncertainties of performance	KTH Library database	"Water Sensitive Urban Design" maintenance
Jonkman & Dawson	2012	Issues and Challenges in Flood Risk Management - Editorial for the special issue on flood risk management	Water	Academic article	Netherlands & UK	Flood management systems	Flood protection	Challenges in flood risk management	addresses challenges including management & maintenance, increase in extreme events continue to impact the aging & failing infrastructure and highlight their vulnerability.	From reference	

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Flynn et al	2012	Operation and Maintenance Assessment for Structural Stormwater BMPs	World Environmental and Water Resources Congress	Academic article	USA	**BMP**, GI, LID	extended detention basins, wet ponds, stormwater wetlands, sand filters, bio-retention practices, vegetated filter strips, wet/dry swales	maintenance review of several municipalities/projects, USA, challenges and perceptions of maintenance.	highlights the importance of context - local climate & ecosystem, difference between public & private managers, costs are so variable, lack of standardized methods for reporting/inspection, continuous maintenance, costs, activities, reporting	From reference	
Keeley et al	2013	Perspectives on the Use of Green Infrastructure for Stormwater Management in Cleveland and Milwaukee	Environmental Management	Academic article	USA	**GI**, SCM, LID, SUDS, WSUD	retention ponds, rainwater harvesting, green roofs, porous pavement, bioswales	Case studies of Cleveland and Milwaukee (USA), policy and governance integration	Literature review and interviews with municipal actors, understanding policy challenges (funding, political support, regulatory framework) for integrating GI, discusses public perception, governance fragmentation, and maintenance challenges	From reference	
Erickson et al	2013	Optimizing Stormwater Treatment Practices	Springer	Textbook	USA	**STP**	sedimentation, filtration, infiltration, and biologically enhanced practices - wet ponds, dry ponds, infiltration basins & trenches, constructed wetlands, permeable pavement, etc	design, implementation, and maintenance guidance.	Using ch. 4 (detailed descriptions of STPs), ch. 13 (maintenance). Maintenance chapter discusses specific maintenance requirements for different STPs, with activities, equipment, frequency, and costs.	Google scholar	stormwater management maintenance

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US EPA	2013	The Importance of Operation and Maintenance for the Long-Term Success of Green Infrastructure	US EPA	Grey literature	USA	**GI**, LID	stormwater management systems	Operation and maintenance review for GI stormwater management, includes comparisons with conventional systems, and case studies of projects. Discusses challenges of maintenance.	assessment of many cases throughout the USA regarding costs, O&M plans, responsibilities, and frequency of activities. Challenges discussed: uncertainties during planning stages - lack of information on O&M costs, lack of comprehensive external funding programs.	EPA Website	
Houle et al	2013	Comparison of maintenance cost, labor demands, and system performance for LID and conventional stormwater management	Journal of Environmental Engineering	Academic article	USA	**LID, SCM**	LID: conventional - vegetated swale, wet pond, dry pond, LID - sand filter, subsurface gravel wetland, bioretention system, and porous asphalt pavement	6-year research study of SCMs for maintenance requirements.	Study of 7 SCMs to assess maintenance costs, labour needs, and performance. found that maintenance tasks often start reactive and then transition to proactive, simplifying maintenance activities lowers costs over the lifetime, maintenance costs tended to be 4-19% of capital costs.	NOAA GI Database	Maintenance, LID
Fletcher et al	2014	SUDS, LID, BMPS, WSUD and more - the evolution and application of terminology surrounding urban drainage	Urban Water Journal	Academic article	USA & Australia	SUDS, LID, BMP, WSUD, GI, IUWM, SCM	Urban drainage	Terminology and typology of sustainable systems.	Considers both spatial and temporal trends of terminology, and the definitions of them. Discusses how the informal nature of the development of these terms leads to confusion and ambiguity	From reference	
Ellis et al	2014	Low impact development in coastal South Carolina: A planning and design guide	North Inlet-Winyah Bay National Estuarine Research Reserves	Grey literature	USA	**LID**, GI, BMP	bioretention, permeable pavement, green roofs, rainwater harvesting, dry & wet detention ponds, wetlands, infiltration channels, open channels, filtering systems	design, implementation, and maintenance guidance.	Good overview of types of practices. Maintenance section includes likely tasks, frequency, troubleshooting, and recommends involvement and inspection by specialists.	NOAA GI Database	Maintenance, grey literature

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Woods Ballard et al	2015	CIRIA SuDS Manual	CIRIA	Grey literature	UK	**SUDS**, WSUD	SuDS - swales, green roofs, infiltration systems, filter strips/drains, bioretention systems, trees, pervious pavements, detention basins, ponds/wetlands	design, implementation, and maintenance guidance, includes both overview of the concept and technical specifications.	Each chapter goes into detail of each type of NBS/SUDS, with technical detail and maintenance chapters for each type, also chapter 32 operation and maintenance, provides specifics of activities, frequencies, costs.	Google	London SUDS Manual
Vineyard et al	2015	Comparing Green and Grey Infrastructure Using Life Cycle Cost and Environmental Impact: A Rain Garden Case Study in Cincinnati, OH	Journal of the American Water Resources Association	Academic article	USA	**GI**	rain garden	Comparison of sustainable (rain gardens) and conventional systems, using LCA	Results of the LCA favour the rain garden: dramatically reduce impacts in almost all categories, and benefits for both eutrophication and global warming. Cost aspects show that rain gardens have far lower start-up costs (and shorter start-up time) but more intensive lifetime maintenance needs.	Google scholar	green infrastructure cost assessment
Sharma et al	2016	Water Sensitive Urban Design: An Investigation of Current Systems, Implementation Drivers, Community Perceptions and Potential to Supplement Urban Water Services	Water	Academic article	Australia	**WSUD**, IUWM, SUDS, BMP, LID, GI	general, urban	Barriers to WSUD, community perceptions	Barriers discussed: lack of clear technical and economic justification for implementation, poor implementation by contractors - lack of oversight during construction, lack of funding, reluctance to assume responsibility for O&M, lack of monitoring, competing objectives of multi-functionality	KTH Library database	"Water Sensitive Urban Design" maintenance

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Kabisch et al	2016	Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action	Ecology and Society	Academic article	Germany	**NBS**, GI, ecosystem-based adaptation, climate change adaptation	General, urban	Barriers to sustainable systems	Policy changes and the use of third-party NBS practitioners to increase implementation. Challenges discussed: uncertainties and risk of implementation, changes in administration and policy mean allocation of funds can change, governance fragmentation, city budgets focused on economic growth more than urban green space expansion.	Google scholar	Nature based solutions and maintenance
Cohen-Shacham et al	2016	Nature-based solutions to address global societal challenges	IUCN	Grey literature	Global	**NBS**, GI, ecosystem-based adaptation, climate change adaptation	restored & constructed wetlands, green roofs, rain gardens, vegetated swales, living shorelines, forest conservation	Overview of the NBS concept, with many case studies and implementation guidance	Definitions, principles, evolution, and frameworks of NBS. Explores NBS in varying context, from policy to best implementation approaches. Use of case studies to build on first half of document.	Google scholar	Nature based solutions
Gibbons	2016	Urban rainwater. A liquid asset	Ri-vista	Academic article	UK	**SUDS**, GI	general, urban	Importance of sustainability in urban drainage systems	discusses the conflation of SUDS maintenance and site maintenance, complexities & uncertainties surrounding maintenance as an excuse to not implement SUDS	Google scholar	Olympic Park suds maintenance

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Hoang & Fenner	2016	System interactions of stormwater management using sustainable urban drainage systems and green infrastructure	Urban Water Journal	Academic article	UK	**SuDS**, GI	urban drainage systems	Analysis of system interactions (both functional and relational) of SuDS/GI and the wider urban system (i.e., connected grey infrastructure, etc), barriers/challenges of SUDS	Discusses the interdependencies during both "normal" conditions, and storm event conditions. Challenges discussed: difficulties with integrating SUDS into existing infrastructure systems, strong dependency of efficacy on maintenance, disconnect between planning and active management of drainage systems	From reference	
Dong et al	2017	Enhancing future resilience in urban drainage system: Green versus grey infrastructure	Water Research	Academic Article	China	**GI**, UDS	green roof, permeable pavements, storage tanks	Comparison of sustainable and conventional systems	Analyses the resilience of green and grey infrastructure, finds that GI has a better adaptability to most future scenarios, although both green and grey can contribute to future resilience of the urban drainage system	Google scholar	grey versus green infrastructure
World Bank	2017	Implementing nature-based flood protection	World Bank	Grey literature	Global	**NBS**, GI, SuDS, ecosystem-based adaptation, climate change adaptation	flood protection	Overview of the NBS concept, with many case studies and implementation guidance	Definitions, principles, evolution, and frameworks of NBS. Explores NBS in varying context, from policy to best implementation approaches.	From reference	
Haghighatafshar et al	2017	Efficiency of blue-green stormwater retrofits for flood mitigation - Conclusions drawn from a case study in Malmö, Sweden	Journal of Environmental Management	Academic article	Sweden	**BGI, SCM**	green roofs, soakaways, bioswales, porous pavement, bioretention and infiltration practices	Case study of Malmö, Sweden, efficiency of BGI	findings indicate that BGI can be very effective for local pluvial flooding, but less effective in preventing flooding in very dense urban areas, generally due to inflows from upstream neighbourhoods	KTH Library database	blue-green stormwater

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Melville-Shreeve et al	2017	State of SuDS delivery in the United Kingdom	Water and Environment Journal	Academic article	UK	**SuDS**	general, urban	Barriers to sustainable systems	questionnaire/ interviews with private & public actors involved in SuDS development. Barriers discussed: unclear maintenance needs, need for stronger regulatory requirements, lack of knowledge/awareness by developers, unclear adoption & management responsibilities	From reference	
Davis & Naumann	2017	Making the Case for Sustainable Urban Drainage Systems as a Nature-Based Solution to Urban Flooding	Nature-based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice	Academic article	UK, Spain, Netherlands	**SUDS**, BMP, LID, NBS, WSUD	general, urban	Cost-benefit analysis of SUDS	Uses examples from UK (Leeds/London) and Europe (Valencia/Netherlands). Reviews of best approaches to SUDS installation for urban flooding. Focus on costs, funding, and policy frameworks, benefits of SUDS	KTH Library database	Nature based solutions, urban
Dhakal & Chevalier	2017	Managing urban stormwater for urban sustainability: Barriers and policy solutions for green infrastructure application	Journal of Environmental Management	Academic article	USA	**GI**, LID, WSUD, SUDS	green roofs, permeable pavements, rain gardens, vegetated swales, etc	Barriers to sustainable systems, policy and governance integration	Suggests alternative governance, education & incentives programs. Barriers: constitutional & regulatory barriers, lack of design & maintenance standards, lack of financial incentives, lack of public engagement, pro-grey mindset, lack of awareness of GI, risk aversion, hesitation to take maintenance responsibility	From reference	
Guo	2017	Urban Flood Mitigation and Stormwater Management	CRC Press	Textbook	USA	**LID**	rain gardens, infiltration strip, porous pavement, bioswales, retention ponds,	design, implementation, and maintenance guidance	Using ch. 1 (overview), ch. 13 (detention basins - mentions maintenance), ch. 17 (Low-impact development)	KTH Library Database	Maintenance, urban flood management system

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Fitzgerald & Laufer	2017	Governing green stormwater infrastructure: the Philadelphia experience	The International Journal of Justice and Sustainability: Local Environment	Academic article	USA	**GI**	permeable pavement, rain gardens, bioswales, rainwater harvesting, buffer strips, green roofs,	Case study of Philadelphia, USA.	Philadelphia was one of the first cities in the USA to commit to relying on GI for certain EPA targets. Focuses on governance & policy and lessons learned.	KTH Library Database	Grey vs green stormwater
Blecken et al	2017	Stormwater control measure (SCM) maintenance considerations to ensure designed functionality	Urban Water Journal	Academic article	USA & Sweden	**SCM**, BMP, SUDS, WSUD, LID, GI	wet ponds, constructed stormwater wetlands, bioretention, infiltration, permeable pavement, swales, rainwater harvesting systems	Maintenance needs for various SCMs, barriers for sustainable systems	SCMs often suffer from a lack of maintenance, discusses consequences of improper maintenance and reasons for neglect. Challenges discussed: communication, unclear responsibilities, lack of technical knowledge, lack of funding	From reference	
Aerts	2018	A Review of Cost Estimates for Flood Adaptation	Water	Academic article	Netherlands	**NBS**, SuDS	river widening/dredging, soft bank protection, constructed wetlands, in-line (river) detention areas, coastal: beach nourishment, dune restoration, artificial reefs urban: green roofs, green zones	Cost-effectiveness of flood adaptation measures, several case studies	Literature review to assess a variety of flood protection/ adaptation measures of costs, both grey and green, including maintenance costs. Uncertainties for frequency of maintenance over time (i.e., aging structures), leading to uncertainties in costs over the life, lack of design standards	Google scholar	Flood adaptation costs
Qiao et al	2018	Challenges to implementing urban sustainable stormwater management from a governance perspective: a literature review	Journal of Cleaner Production	Academic article	Sweden	**SSM**, NBS, GI, LID, SuDS, WSUD, Sponge City	general, urban	Challenges to implementing SSM, focus on policy and governance	Challenges discussed: Unclear leadership responsibilities, lack of funding, evidence of costs & efficiency, space, knowledge, regulatory framework and standards, collaboration with researchers, and the difficulties in stakeholder participation	KTH Library Database	Urban stormwater management, challenges

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Ashley et al	2018	Including uncertainty in valuing blue and green infrastructure for stormwater management	Ecosystem Services	Academic article	UK	**BGI**, SuDS, ES,	general, urban	Cost-benefit analysis, decision-making tool (BEST)	how to use the BEST tool and the importance of understanding uncertainty & flexibility in planning with BGI. Challenges discussed: lack of clear guidance to handle uncertainties in the design & operation of BGI	From reference	
Thorne et al	2018	Overcoming uncertainty and barriers to adoption of Blue-Green Infrastructure for urban flood risk management	Journal of Flood Risk Management	Academic article	USA	**BGI,** GI, SuDS, BMP	stormwater management such as green roofs, 'green streets', etc.	Case study of Portland, USA, uncertainty	Hesitations for implementing urban BGI for stormwater management. Barriers discussed: future governing structures, populations, and land use, who pays for implementation/ maintenance, public perception, effectiveness, and future events	From reference	
Everett et al	2018	Delivering Green Streets: an exploration of changing perceptions and behaviours over time around bioswales in Portland	Journal of Flood Risk Management	Academic article	USA	**BGI**, GI, SuDS	bioswales	Case study of Portland, USA, public perceptions	investigation of resident's perceptions & behaviours around local bioswales, of different "ages". Results show little correlation between age and awareness/ opinion of residents. Challenges discussed: lack of awareness and understanding, litter & untidy appearance, perceived regularity & efficacy of maintenance, bugs, residents performing own maintenance.	KTH Library Database	GI, Portland

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Mullulay	2019	WSUD Asset Management Operation and Maintenance	Approaches to Water Sensitive Urban Design: Potential, Design, Ecological Health, Urban Greening, Economics, Policies, and Community Perceptions	Textbook	Australia	**WSUD, SCM**, LID, GI, SUDS, SC, BMP	permeable pavement, bioretention basins, bioswales, wetlands, etc	design, implementation, and maintenance guidance	chapters cover history of WSUD approaches, design guidelines, ecological health, economic benefits, urban development, capacity building, community perceptions, and case studies	KTH Library Database	Water sensitive urban design
Johns	2019	Understanding barriers to green infrastructure policy and stormwater management in the City of Toronto: a shift from grey to green or policy layering and conversion?	Journal of Environmental Planning and Management	Academic article	Canada	**GI**, LID	general, urban	Case study of Toronto, Canada, barriers to transition to sustainable systems	Focuses on governance & policy, through interviews. Barriers discussed: funding, inter-departmental cooperation, leadership/ responsibility, lack of expertise, local conditions, lack of public engagement, dominant grey values	KTH Library Database	Grey vs green stormwater
Huang et al	2019	Nature-based solutions for urban pluvial risk management	Wires Water	Academic article	China	**NBS**, SUDS, LID, BMP, WSUD, GI, sponge city	general, urban	Terminology, barriers and benefits of NBS.	discusses the similarities & difference of terminology, concludes NBS tend to be less effective under extreme weather events, but much more effective in small-scale events	Wires water	"sustainable engineering of water"
Somarakis et al	2019	Nature Based Solutions Handbook	ThinkNature (EU Horizon Project Funded)	Grey literature	EU	**NBS**	general	Overview of the NBS concept, with implementation guidance	Challenges discussed: Lack of ready to use technologies, knowledge silos, lack of evidence and quantification of benefits, insufficient/absent monitoring, lack of funding, lack of coordinated knowledge transfer.	Google	Nature Based solutions guidance document

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Drosou et al	2019	Key Factors Influencing Wider Adoption of Blue-Green Infrastructure in Developing Cities	Water	Academic article	Indonesia	**BGI**, GI, SUDS, WSUD, LID, BMP	infiltration wells, retention ponds, permeable pavement, bioswales, rain gardens, green roofs, rainwater harvesting systems	Case study of Semarang, Indonesia, barriers and drivers to sustainable systems, stakeholder & public perceptions	socio-political barriers to adoption of BGI, focusing on developing or low- and middle-income countries. Barriers discussed: funding, public awareness, fragmentation of policy frameworks, system inefficiency, lack of inclusion in the planning process	From reference	
Sarabi et al	2019	Key Enablers of and Barriers to the Uptake and Implementation of Nature-Based Solutions in an Urban Setting: A Review	Resources	Academic article	Netherlands	**NBS**	general, urban	Barriers and drivers to sustainable systems	Challenges discussed: financial resources, path dependency, institutional fragmentation, inadequate regulations, uncertainty effectiveness, limited land & time availability	From reference	
Wihlborg et al	2019	Assessment of barriers and drivers for implementation of blue-green solutions in Swedish municipalities	Journal of Environmental Management	Academic article	Sweden	**BGI**, NBS, SUDS, LID, WSUD, sponge city, open stormwater management	general, urban	Case studies in Sweden, barriers and drivers to sustainable systems	Barriers discussed: economy, lack of expertise, unclear responsibilities, legislation, municipal organisation, urban densification, more pressing issues/lack of time	From reference	
Williams et al	2019	Residents' perceptions of sustainable drainage systems as highly functional blue green infrastructure	Landscape and Urban Planning	Academic article	UK	**SuDS**, **BGI**	rain gardens, green roofs, bioswales, retention ponds, filter strips, wetlands	Case studies in UK, public perceptions	survey to residents to understand their awareness and perception of SuDS, Challenges discussed: litter/pests/untidiness perception, costs of maintenance	From reference	

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Lashford et al	2019	SuDS & Sponge Cities: a comparative analysis of the implementation of pluvial flood management in the UK and China	Sustainability	Academic article	UK & China	**SuDS, Sponge City**	general, urban	Comparison of Sponge Cities (China) and SUDS (UK), barriers and drivers of sustainable systems	An analysis of the sponge city concept and how it could be applied to UK urban flood management. Challenges discussed: ownership/ responsibility for long-term maintenance, long-term costs not being accounted for from the start, uncertainty of ownership of liabilities	From reference	
DelGrosso et al	2019	Identifying Key Factors for Implementation and Maintenance of Green Stormwater Infrastructure	Journal of Sustainable Water in the Built Environment	Academic article	USA	**GI** (GSI), BMP, SCM, SUDS,	bioretention, permeable pavement, sand filters, infiltration trenches, vegetated swales	Maintenance needs, barriers to sustainable systems	Assessment of maintenance protocols. Challenges discussed: inadequate maintenance affects the performance & longevity of the system, maintenance plans/issues can be more complex compared to conventional systems, lack of documentation of required inspection & maintenance protocols	KTH Library Database	GI, maintenance
Chen et al	2019	Evaluation of the effectiveness of green infrastructure on hydrology and water quality in a combined sewer overflow community	Science of Total Environment	Academic article	USA	**GI**, LID, BMP	Bioretention, permeable pavement, green roofs, rain barrels,	Hydrologic modelling for effectiveness of GI	How GI impacts water processes/quality in CSO communities, provides context for installation of some NBS, cost of maintenance for these types of NBS compared to installation costs, based on a 20-year design life.	NOAA GI Database	NBS, maintenance, urban flooding
Webb et al	2019	Nature-based solutions for coastal highway resilience: an implementation guide	US Department of Transportation, Federal Highway Administration	Grey literature	USA	**NBS**	general, flood adaptation, living shorelines	design, implementation, and maintenance guidance	implementation guide for NBS for coastal roads & bridges, includes sections on maintenance & monitoring, and costs	NOAA GI Database	Maintenance, grey literature

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Drescher & Sinasac	2020	Social-psychological Determinants of the Implementation of Green Infrastructure for Residential Stormwater Management	Environmental Management	Academic article	Canada	**GI** (GSI), BMP	permeable pavement, soakaway, rainwater harvesting, green roofs, etc (residential/lot-level measures)	Case study in Kitchener, Canada, public perceptions & beliefs	survey for residents' perceptions and willingness to pay/participate in sustainable stormwater management. Found most residents believe municipal authorities should be solely responsible for installation & maintenance	KTH Library Database	grey vs green, stormwater
Esmail & Suleiman	2020	Analysing Evidence of Sustainable Urban Water Management Systems: A Review through the Lenses of Sociotechnical Transitions	Sustainability	Academic article	Italy & Sweden	**SUWM**, B/GI, LID, SuDS, BMP, NBS, IUWM, SCM, WSUD, sponge city	ponds, wetlands, porous pavements, swales, trenches, open canals, green roofs, bio-retention systems, etc - open spatial systems, nature-based facilities	Barriers and drivers for sustainable systems, policy and governance instruments	Challenges: complex terminology can cause confusion & miscommunication, lack of access to technical knowledge & modelling tools, over-representation of public actors results in management/ responsibility issues, lack of framework or analyses on long-term monitoring & evaluation, fragmentation	From reference	
Ferreira et al	2020	Stakeholders' Engagement on Nature-Based Solutions: A Systematic Literature Review	Sustainability	Academic article	Portugal	**NBS**, GI, Biophilic Urbanism (BU)	general, urban	Stakeholder participation & perceptions of NBS	Challenges discussed: perceived risks by citizens & stakeholders, such as maintenance costs, dirtiness & damage, invasive species, contamination, need for skilled maintenance crew, continuity	KTH Library Database	Nature based solutions, maintenance
Alves et al	2020	Exploring trade-offs among the multiple benefits of green-blue-grey infrastructure for urban flood mitigation	Science of the Total Environment	Academic article	St Maarten, Caribbean	**BGI**, BMP, LID, WSUD, SuDS, EBA, NBS	rainwater harvesting systems, open channels, infiltration basins, pervious pavements	Case study in Sant Maarten, cost-benefit analysis, cost-effectiveness	Investigates the optimisation of systems to find the ideal combination of co-benefits, performance, and costs. too many co-benefits can impact performance of main purpose	From reference	

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Månsson & Persson	2020	Ekostaden Augustenborg - erfarenheter och lärdomar	Arkus	Book	Sweden	**blue-green stormwater management**, open stormwater system	green roofs, retention ponds, "open" stormwater system	Case study of Ekostaden Augustenborg - Malmö, Sweden	review of Ekostaden Augustenborg after 20 years - lessons learned, experiences, etc. Challenges discussed: public perception, lack of clarity re responsibility for maintenance, lack of technical knowledge/ misconceptions about NBS	KTH library database	Ekostaden Augustenborg
Wamsler et al	2020	Environmental and climate policy integration: Targeted strategies for overcoming barriers to nature-based solutions and climate change adaptation	Journal of Cleaner Production	Academic article	Sweden	**NBS**, ecosystem services, climate-change adaptation	parkland, urban regeneration, flood protection	Case studies in Sweden, barriers and solutions for NBS, policy and governance integration	Provides potential solutions for how to create a more systematic approach at the municipality level.	KTH Library Database	Nature-based solutions, barriers
Cotterill & Bracken	2020	Assessing the Effectiveness of Sustainable Drainage Systems (SuDS): Interventions, Impacts and Challenges	Water	Academic article	UK	**SuDS**, BGI, NBS,	rainwater harvesting system, tree pits	Case study in UK, public perceptions, performance	effectiveness of SUDS through establishment of a monitoring program. challenges: lack of community engagement, issues with monitoring data collection, maintenance of monitoring equipment, difficulty in quantifying benefits	From reference	
Green et al	2020	Green infrastructure: the future of urban flood management?	Wires Water	Academic article	UK & China	**GI**, NBS, BGI, SUDS, LID, BMP, WSUD, sponge city	bioswales, green roofs, rain gardens, permeable pavements, rainwater harvesting, detention ponds	Challenges and opportunities with GI	Challenges discussed: lack of routine measurements & monitoring, accessibility of facilities, misdiagnosing/not noticing maintenance needs until significant loss in performance or aesthetics	Wires water	sustainable engineering of water

Author	Year	Title	Publication/ Publisher	Type of literature	Location	Terminology	Stormwater system components	Topic of Discussion	Content	Source	Search Terms
Li et al	2020	Identifying enablers ad barriers to the implementation of the Green Infrastructure for urban flood management: A comparative analysis of the UK and China	Urban Forestry & Urban Greening	Academic article	UK, China	**GI, SUDS, Sponge cities**, LID	general, urban	Comparison of Sponge Cities (China) and SUDS (UK), barriers and drivers of sustainable systems	Interviews with stakeholders to understand barriers: funding, responsibility for maintenance, lack of relevant monitoring data, fragmented governance and unclear responsibilities, emphasis on exclusively costs/economic benefits, lack of technical understanding in decision-makers	Google scholar	barriers of green infrastructure in flood management
Brauman et al	2021	Producing valuable information from hydrologic models of nature-based solutions for water	Integrated Environmental Assessment and Management	Academic article	Brazil/South America	**NBS**, GI	watershed-level management	Case studies in South America, hydrologic modelling for effectiveness of NBS	Assesses salience, credibility, and relevance of knowledge gathering for NBS, investigates stakeholders in three categories: advocates, implementers, and analysts	NOAA GI Database	Nature-based solutions
Brillinger et al	2021	Integrating nature-based solutions in flood risk management plans: A matter of individual beliefs?	Science of the Total Environment	Academic article	Germany	**NBS**	general, urban, flood adaptation	Case study in Germany, stakeholder perceptions & beliefs	Investigates why decision-makers do or do not implement NBS, from the perspective of flood risk management, findings indicate NBS are not favoured: primary focus is risk avoidance, not long-term planning, bias towards conventional systems, cost-oriented in decision-making	From reference	

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Dorst et al	2021	Structural conditions for the wider uptake of urban nature-based solutions - A conceptual framework	Cities	Academic article	Netherlands	**NBS**	bioswales, river restoration, ecological water banks, buffer lakes, permeable paving	Case studies in Scotland and France, structural conditions, policy and governance	Analysis of structural conditions that influence the implementation of NBS - existing infrastructure, policy and regulations, knowledge/expertise, funding, etc. Challenges discussed: existing physical infrastructure, silo-thinking in governance, lack of policy frameworks and expertise, funding structures that favour grey/structural solutions	KTH Library Database	Nature-based solutions, urban
Han & Kuhlicke	2021	Barriers and Drivers for Mainstreaming Nature-Based Solutions for Flood Risks: The Case of South Korea.	International Journal of Disaster Risk Science	Academic article	South Korea	**NBS**, sustainable flood risk management, LID	general, urban, flood adaptation	Case study in South Korea, barriers and drivers for sustainable systems, stakeholder perceptions	Attitudinal and contextual barriers and drivers of NBS for flood risks. Challenges discussed: insufficient quantification of risk management, spatial constraints, NBS seen as add-on option, perceived higher maintenance and implementation costs,	Google Scholar	NBS Maintenance drivers
Bridges et al	2021	International guidelines on nature and nature-based features for flood risk management	USACE	Grey literature	USA	**NNBF** (natural and nature-based features)	flooding management (coastal & fluvial, beaches, reefs, wetlands, islands, submerged aquatic vegetation)	design, implementation, and maintenance guidance	extensive guidance for implementation and monitoring of NNBF, includes discussion of risk & uncertainty, and many case studies from around the world	From reference	USACE NNBF Guidelines
Matsler et al	2021	A "green" chameleon: Exploring the many disciplinary definitions, goals, and forms of "green infrastructure"	Landscape and Urban Planning	Academic article	USA	**GI**, LID, BMP, SUDS, BGI, WSUD, NBS, sponge city	general	Terminology and typology of GI.	literature review focusing on the terminology & typology, academic vs practical application, and challenges related to the multiple concepts with similar meanings around GI.	KTH Library database	green infrastructure, definition

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Wright et al	2022	Improper Maintenance Activities Alter Benefits of Urban Stormwater Treatment in a Temperate Constructed Wetland in NSW, Australia	Frontiers in Environmental Chemistry	Academic article	Australia	**SCM**	constructed wetlands	Case study in NSW, Australia, maintenance needs & impacts	investigation into constructed wetlands and the impact on performance of improper maintenance.	KTH Library database	WSUD maintenance
Moin et al	2022	Effect of Visibility on Maintenance Investment and Consequent Performance of Urban Stormwater Control Measures	Journal of Sustainable Water in the Built Environment	Academic article	USA	**SCM**	wetlands, wet ponds, bioretention cells	Case study in North Carolina, USA, maintenance needs, performance	assesses if visibility of SCMs affects the maintenance received and therefore on the performance. Findings: smaller SCMs have higher maintenance costs, communication between design and maintenance authorities are essential.	KTH Library database	stormwater control measure maintenance