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Community-centered instrumentation and monitoring of nature-based solutions for urban stormwater control

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Climate change is increasing the frequency and severity of extreme precipitation events, requiring new ways of managing stormwater, particularly in urban areas. Nature-based solutions (NBS) have become increasingly popular to provide distributed stormwater storage while supporting urban biodiversity and access to nature. However, long-term monitoring of the hydrological performance of NBS is limited. To date most literature has focused on monitoring methodologies for specific sites and types of NBS, use of remote sensing and modeling for large-scale assessments, or measuring benefits of NBS for urban heat mitigation. More comprehensive and consistent measurement strategies are needed to understand the effects of distributed NBS on urban hydrology at the regional scale, and improve the design, maintenance, and adoption for community-centered stormwater management. To address these gaps, we review available literature on measurement methods, summarize these methods and provide specific recommendations for instrumentation and *in situ* monitoring of common types and scales of urban NBS. Based on our findings on performance monitoring for individual NBS sites, we extend recommendations for consistent hydrological assessment of distributed NBS at regional scale and the efficacy of NBS in reducing community flooding impacts. These recommendations are particularly applicable for municipalities, researchers and community-based organizations who are now leading the planning and implementation of community-centered NBS systems in many areas.

KEYWORDS
stormwater management, green infrastructure, monitoring, instrumentation, flood reduction, nature-based solutions

1 Introduction

By 2050, 68% of the world's population is expected to live in urban areas, resulting in an additional 2.5 billion urban residents over the next 25 years (United Nations, Department of Economic and Social Affairs, Population Division, 2019). As our cities grow, so does the number of roads, buildings and parking lots, increasing the impervious cover of the land, which in many cities is already greater than 40% (Tabari, 2020). With more impervious surface, stormwater runs more quickly off roads and roofs and into the drainage system, which can become easily overwhelmed, resulting in water quality degradation and flooding. As extreme precipitation events become more frequent due to climate change (Nowak and Greenfield, 2012), urban flooding is expected to increase, especially in under-resourced communities, making stormwater management even more critical.

Nature-based solutions (NBS) have become an increasingly popular means of managing stormwater runoff. NBS are defined by the International Union for Conservation of Nature as measures that "protect, sustainably manage, and restore natural and modified ecosystems" to address environmental challenges and benefit both people and nature (Nature-Based Solutions IUCN, n.d.). A number of different terms are used to describe systems that integrate natural and human-built infrastructure for stormwater management (Environmental Policy Innovation Center, 2024). These include green infrastructure (US EPA, O, 2015b), natural infrastructure (Institute for Resilient Infrastructure Systems, n.d.), natural flood management (University of Reading, n.d.), low impact development (LID) (US EPA, O, 2015a), green stormwater infrastructure (GSI) (Clean Water Education Partnership, 2023), stormwater best management practices (BMPs) (Southwestern Pennsylvania Commission Water Resource Center, n.d.), and sustainable urban drainage systems (SuDS) (British Geological Survey, n.d.). Here we use the term *nature-based solutions* as an umbrella concept encompassing all approaches that use open land and natural ecosystems to address urban stormwater challenges. NBS capture and absorb stormwater before it enters the drainage system, reducing the burden on gray stormwater infrastructure during heavy rain events and replenishing local groundwater supplies. NBS also provide many other key ecosystem services, including improving air quality, reducing the urban heat island effect, and increasing biodiversity (Chang et al., 2017). We focus specifically on community-centered NBS, which we define as NBS projects led by or in partnership with local communities, non-profit organizations, or community organizations to address local challenges.

Despite its increasingly popular use for stormwater management, limited guidance is available to establish standard methods for monitoring different types of NBS and documenting their effects on local hydrology and stormwater capture. Existing literature has focused mainly on instrumentation and monitoring of a single site with one specific type of NBS and does not consider designs for instrumentation that can be applied across a wide variety of NBS across different scales and regions (Catalano de Sousa et al., 2016; Woznicki et al., 2018; Feldman et al., 2019; Fuentes et al., 2021; Meixner et al., 2021; Xie et al., 2021). Regional assessments to date have used satellite-based data products or other remote sensing methods, and do not include methods for *in situ* monitoring of NBS (Stewart et al., 2017; Lim and Welty, 2018; Taramelli et al., 2019; Furberg et al., 2020). Prior reviews of the methodologies and frameworks for monitoring NBS have largely focused on quantifying the impact on urban heat mitigation or benefits to urban biodiversity, and not the hydrological benefits (Chen et al., 2016; Bartesaghi Koc et al., 2018; Saaroni et al., 2018).

Measuring the hydrological dynamics of NBS and resulting benefits for flood reduction is critical to improving NBS design, informing maintenance strategies, and encouraging adoption of NBS by both communities and public officials (Ahern, 2007; Geberemariam, 2017; Gordon et al., 2018). However, monitoring of NBS is inconsistent, which makes it difficult to compare effectiveness of alternate NBS strategies and generalize the benefits of NBS to municipal or regional scales (Kerkez et al., 2016; Monteiro et al., 2020; Sun et al., 2020). Consistent methods of measuring the hydrological benefits of NBS are necessary to establish standard metrics and benchmarks for performance (Geberemariam, 2017). Specific guidance for monitoring of community-centered NBS performance is also needed because NBS measurements have been predominantly performed by universities, consultants, or government agencies, but many community organizations and non-profits are now leading the implementation and monitoring of community-scale NBS. To fill these gaps, we review the literature on hydrological monitoring of NBS and derive general recommendations for (1) instrumenting and monitoring different types and scales of community-centered NBS, and (2) use of the resulting data to track long-term performance, inform maintenance strategies, and design regional NBS solutions for climate resilience.

2 Objectives and methods for measuring the performance of nature-based solutions

Soil moisture and groundwater level measurements are important for many types of NBS and are frequently used in monitoring civic infrastructure projects (Fassman-Beck et al., 2013; Kazemi, 2014; Grey et al., 2018; Feldman et al., 2019; Alizadehtazi and Montalto, 2020; Mason et al., 2021). Soil moisture is normally measured using sensors that detect the volumetric water content of the surrounding soil. Soil moisture sensors are frequently used by researchers to assess the performance of green roofs (Versini et al., 2016; Ouellet et al., 2021), rain gardens (Potter, 2023), and urban natural areas (Phillips et al., 2019). While soil water content is normally a small fraction of the total stormwater storage provided by NBS, soil moisture measurements can be used to determine the impact of antecedent soil moisture on the response to rain events and monitor *in situ* conditions for plant growth (Phillips et al., 2019; Tu et al., 2020; Xie et al., 2021). For broader areal measurements of soil moisture, geophysical techniques such as Electrical Resistivity Tomography (ERT) are often appropriate (Brunet et al., 2010; de Jong et al., 2020). ERT measures electrical resistivity between multiple electrodes spaced across a site (de Jong et al., 2020). As soil conductivity increases with water content, the soil moisture is determined from resistivity measurements using an empirical equation (Brunet et al., 2010). This method is more expensive and labor intensive than point soil sensors, so it is normally used to obtain spatial data across a site on an infrequent basis (e.g., annually or seasonally).

Due to the importance of site hydrogeological conditions, measurements of infiltration rates and soil characteristics provide useful data for both designing NBS and assessing their performance (Schlea et al., 2014; Lewellyn et al., 2016). Infiltration tests (American Society for Testing and Materials, 2020) and soil characterization, such as grain-size distributions, porosity, and soil type, are frequently conducted during site investigation as part of the NBS design process. Time-series measurements of water levels across a site are used to assess (eco) hydrological dynamics. Groundwater levels are frequently measured within a variety of NBS, including rain gardens (Schlea et al., 2014;

Mason et al., 2021; Potter, 2023), infiltration trenches (Lewellyn et al., 2016), bioretention cells (Winston et al., 2016), and natural areas (Hernandez Gonzalez et al., 2019). Piezometers are used with a pressure transducer water level sensor (Figure 1), together with soil porosity, to determine the volume of water stored in the subsurface (Potter, 2023). When combined with hydrological modelling, *in situ* data can potentially be used to understand the hydrologic response of NBS to stormwater and the resulting storage time distributions, though both measurements and modelling hydrologic dynamics between the urban environment and NBS remain challenging (Sharma et al., 2020; Qian et al., 2022). Commonly used models for NBS include groundwater modelling with relatively simple representations of surface water (Sharma et al., 2020; Li et al., 2024). This includes ecohydrological models that use land use, soil type, vegetation, and weather data to represent landscape processes, often in a long-term climate context (Castelli et al., 2017; University of Michigan Graham Sustainability Institute, n.d.); and urban hydrology and hydraulic models that estimate stormwater infiltration, runoff, and flow in both natural and engineered parts of the urban environment (Nanía et al., 2015; Korgaonkar et al., 2018; Mignot and Dewals, 2022).

In engineered NBS designed with a discharge or overflow pipe, outflow is frequently measured using a flow meter (Carson et al., 2013; Versini et al., 2016; Ouellet et al., 2021) or a weir and pressure-transducer water level sensor (Winston et al., 2016). Downstream flow within the stormwater drainage system, such as storm sewers, ditches, and receiving streams and rivers, can also be monitored to assess the efficacy of NBS in reducing urban stormwater impacts (Jarden et al., 2016; Boening-Ulman et al., 2022). However, downstream flow is not often measured in NBS performance evaluation as it requires making measurements over much larger scales and within larger-scale controlled infrastructure that is subject to high forces during flood flows. Consequently, such work is primarily done by stormwater agencies and specialized professional contractors, and not directly by NBS researchers or by communities implementing local NBS solutions.

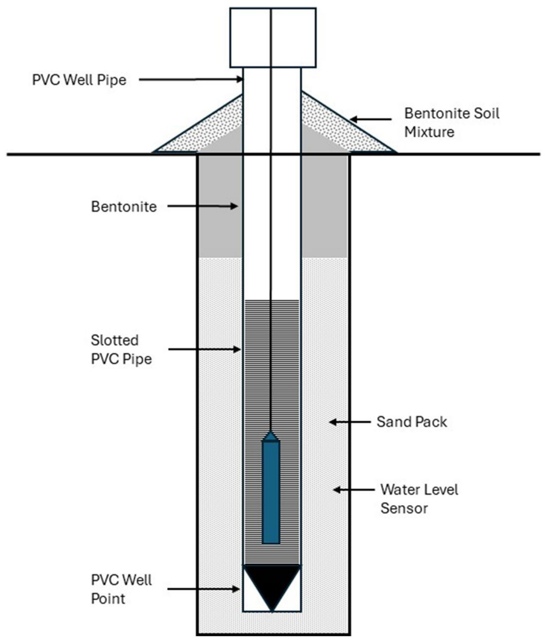

FIGURE 1
Cross section of typical piezometer with groundwater level sensor. Based on drawings provided by Hey and Associates, Inc (2021).

Precipitation measurements are needed for comparison against soil moisture and water level data to complete water budget calculations and evaluate NBS stormwater performance as a function of storm intensity and antecedent *in situ* conditions. Precipitation data collected and published from governmental monitoring stations, such as rain gage data collected by the National Weather Service, are often used to estimate water inputs to NBS sites. However, due to the high degree of heterogeneity in precipitation within a city or region, local precipitation is frequently measured at the NBS installation being monitored (Cristiano et al., 2017; Zhuang et al., 2020). Commonly used methods to measure precipitation at the site scale include classic tipping-bucket rain gages and newer optical rain sensors. Tipping bucket rain gages are available heated, which capture precipitation from rain and snow, and unheated, which only capture rainfall. Optical rain sensors are non-contact and detect and measure rainfall via drop size and frequency using infrared light beams (Bartholomew, 2016). To provide a more complete description of local weather and climate, precipitation measurements can be combined with other meteorological measurements, including temperature, relative humidity, wind speed and direction, and solar radiation. These sensors are often used in newer suites of wireless sensors, such as the Wild Sage environmental sensing system (Catlett et al., 2022).

Current conceptual models for NBS hydrology are primarily based on conventional urban stormwater infrastructure design, and monitoring focuses on traditional stormwater metrics such retention, detention, and infiltration (Beauchamp and Adamowski, 2013; Prudencio and Null, 2018; Li et al., 2019; Zhang et al., 2021). However, detention and retention concepts that are based on impermeable constructed infrastructure do not translate well to NBS involving extensive surface-groundwater interactions and long-term ecosystem dynamics. Because there is no consensus on important attributes of NBS hydrologic function, the metrics reported in NBS literature vary quite considerably. In 26 studies evaluating the performance of different types of NBS, 17 different metrics were used. The most common metrics were reduction in peak flow (Khan et al., 2012; Fassman-Beck et al., 2013; McLaughlin et al., 2014; Schlea et al., 2014; Jarden et al., 2016; Winston et al., 2016; Batalini de Macedo et al., 2019); percent of water retained, captured, or infiltrated; (Carson et al., 2013; Fassman-Beck et al., 2013; McLaughlin et al., 2014; Paus et al., 2015; Lewellyn et al., 2016; Feldman et al., 2019; Cook et al., 2021) and infiltration rate (Kazemi, 2014; Lewellyn et al., 2016; Elliott et al., 2018; Mason et al., 2021; Meixner et al., 2021). Other commonly used metrics include storage volume (Stewart et al., 2017; Batalini de Macedo et al., 2019; Xie et al., 2021), runoff depth (Fassman-Beck et al., 2013; Boening-Ulman et al., 2022), and exfiltration rate (Kazemi, 2014; Grey et al., 2018). This variability in reported metrics makes it difficult to compare the hydrology and benefits of different types and scales of NBS. Existing metrics also fail to capture to the full extent of hydrologic processes in NBS, such as large-scale surface-groundwater interactions and long-term water storage. Beyond individual sites, the conceptual focus on retention, detention and infiltration makes it challenging to aggregate hydrologic dynamics across multiple types and locations of NBS and prevents consistent assessments of regional outcomes for urban hydrology and flood reduction. More consistent instrumentation designs are needed to complete full water budgets for NBS, and new metrics are needed to evaluate the performance of NBS systems as regional stormwater solutions.

3 Recommendations for monitoring of nature-based solutions

3.1 Proposed conceptual framework

To develop systematic recommendations for evaluating hydrologic dynamics in NBS, we first develop a conceptual model classifying NBS based on three major factors: the type or form of NBS, the scale, and the degree of naturalness. These three characteristics influence monitoring needs, including sensor type(s), the number of sensors, and their placement within the NBS to accurately determine both site water balances and effectiveness as stormwater infrastructure (Figure 2). The type of NBS strongly influences the type(s) of sensors required. For example, a constructed surface-water wetland will require surface water level sensors but generally not soil moisture sensors, whereas soil moisture sensors will be critical in measuring water storage in a green roof (Versini et al., 2016; Ouellet et al., 2021). The scale of the NBS impacts the number of sensors required. A larger natural green space will require more sensors to assess the benefits than a small park or community garden. The degree of naturalness impacts both the type and configuration of sensors. We define the degree of naturalness as the extent of natural soil and ecosystems within the site relative to the extent of constructed hard infrastructure. For example, permeable pavement is an entirely engineered system constructed from human-made (artificial) materials, whereas a native parkland or forest is considered entirely natural. NBS with intermediate degrees of naturalness include a mixture of natural and engineered elements, for example a green roof, bioretention basin, or restored wetland with engineering control of water levels. NBS that are engineered may have an outflow pipe that will be useful to instrument and may require additional *in situ* sensors.

3.2 Instrumentation designs for six common classes of nature-based solutions

Based on the key characteristics of form, scale, and degree of naturalness identified in the conceptual model (Figure 2), we selected six common types of NBS for detailed consideration: bioretention basins, rain gardens, green streetscapes, green roofs, nature preserves, and community green spaces. These selected NBS types span commonly used configurations ranging from small features located within individual residential properties to neighborhood-scale land restoration efforts, large municipal projects, and natural areas. Bioretention basins provide an example of semi-natural NBS with some engineered components that provide both surface and subsurface storage and can range in scale from approximately 5–100 m^2 in area, often even larger depending on the contributing catchment area. Rain gardens are similar in design to bioretention basins but tend to include deep-rooted plants and are often at a smaller scale, as they are frequently used in individual-household residential settings. Green streetscapes include several different types of small scale semi-natural NBS that can be implemented individually or, more typically, as part of a larger infrastructure project, e.g., box tree filters along a long stretch of road. Streetscapes include natural vegetation and engineered elements, such as outflow pipes connected to the municipal stormwater system, or may be combined with other infrastructure, such as permeable pavement. Green roofs represent an intermediate scale engineered NBS that provide predominantly subsurface storage and plant transpiration in an engineered soil layer. Nature preserves, including designated natural areas within urban parks, generally have native vegetation and hydrology, and we therefore consider them entirely natural even though the land may

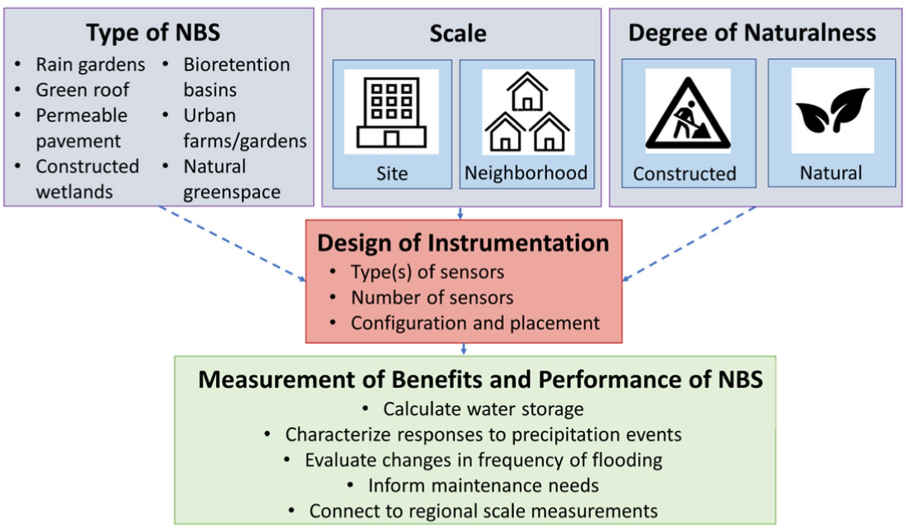

FIGURE 2
Conceptual framework of the factors influencing instrumentation design for monitoring community-centered NBS performance, including NBS type, scale, and degree of naturalness.

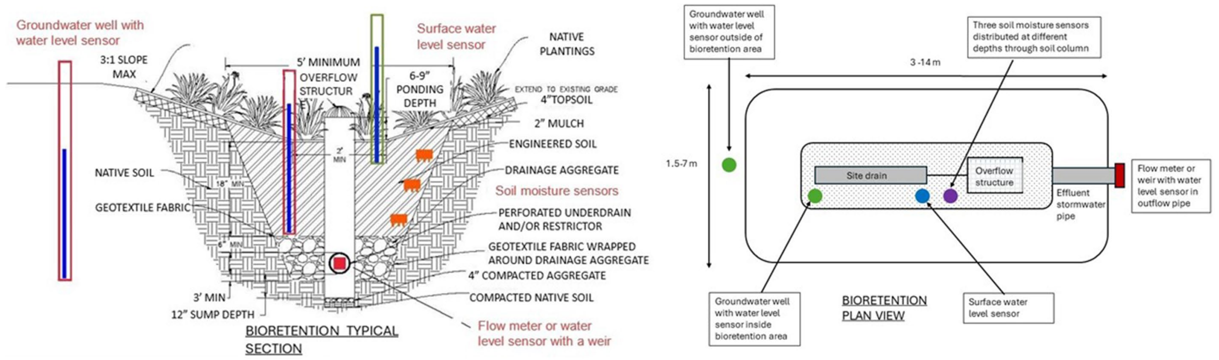

FIGURE 3
Instrumentation designs for bioswale including soil moisture sensors, piezometers with water level sensors, a surface water level sensor and a flow meter. Bioswale section drawing provided by the Delta Institute (Eskin et al., 2021). Plan view based on drawings by American Wick Drain (n.d.).

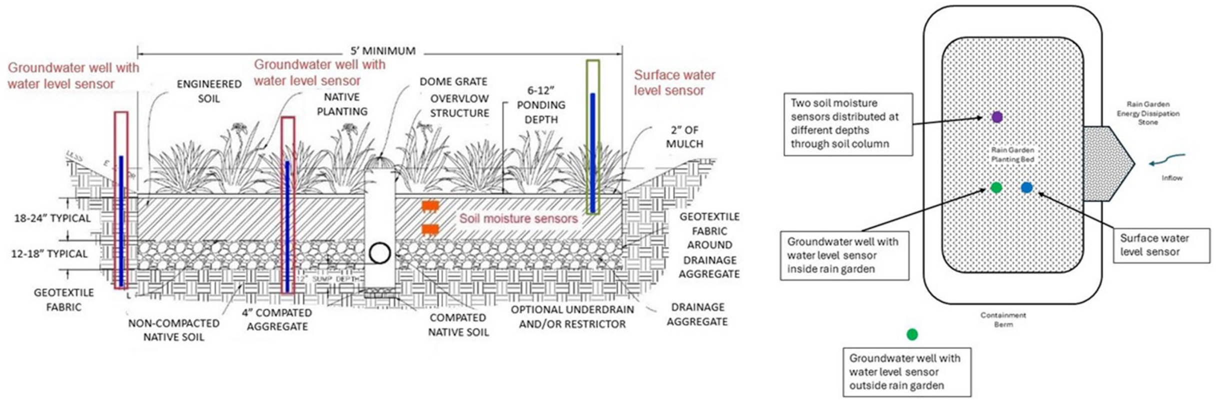

FIGURE 4
Instrumentation designs for rain garden including soil moisture sensors, a surface water level sensor, and piezometers with water level sensors. Rain garden section drawing provided by the Delta Institute (Eskin et al., 2021). Plan view based on drawings by the Milwaukee Metropolitan Sewerage District and Strand Associates, Inc (Kaminski and Bzdusek, 2017).

be intentionally modified or restored. These areas range in size from 1,500 m^2 to over 450,000 m^2. Lastly, community greenspaces include a variety of different forms of NBS that are designed to provide amenities for local communities, including community gardens, local parks, and other recreational areas. Many community greenspaces are embedded within highly urban areas and are designed for multiple purposes, including stormwater storage.

Recommended sensor configurations for each class of NBS are shown in Figures 3–8, and recommended types, numbers, and costs of sensors are provided in Table 1. The number of sensors needed within an NBS system is determined mainly based on the size and scale of the NBS being monitored, as well as site heterogeneity and the degree of data resolution needed for analysis of site hydrology, which is determined based on the monitoring objectives.

Bioretention basins (Figure 3), and rain gardens (Figure 4) require piezometers with water level sensors, surface water level sensors, and soil moisture sensors to estimate the water storage volume (Khan et al., 2012; Schlea et al., 2014; Paus et al., 2015; Winston et al., 2016; Stewart et al., 2017; Batalini de Macedo et al., 2019; Feldman et al., 2019; Cook et al., 2021; Meixner et al., 2021). The spacing between soil moisture sensors depends on the depth of the system, but in general these should be vertically distributed through the soil column (Stewart et al., 2017; Meixner et al., 2021). In some systems, connectivity between surface water and groundwater has been engineered so that surface and groundwater storage can be measured with one piezometer extending above the ground surface. However, in many cases the presence of an unsaturated zone or buried construction debris limits infiltration and causes a disconnect between groundwater and surface water (Shuster et al., 2014), which necessitates both a piezometer and surface water level sensor to accurately measure total storage volume (Batalini de Macedo et al., 2019). In bioretention basins or rain gardens with a defined inlet, inflow is frequently measured with a weir and water level sensor (Batalini de Macedo et al., 2019; Feldman et al., 2019). For those without a clear inlet point, inflow can be estimated using an overland flow collector (Moruza et al., 2021). In bioretention basins with an outflow or overflow pipe, a flow meter or weir and water level sensor can also be installed to measure outflow when there is interest in determining discharge to the drainage system. In low-lying landscapes, there may be concern that the effectiveness of NBS is limited by a shallow regional groundwater table (Zhang and Chui, 2019). Particularly in flat alluvial landscapes, infiltration from bioretention systems can cause the groundwater table outside the system to rise, decreasing available storage (Thomas and Vogel, 2012; Nemirovsky et al., 2015). Where

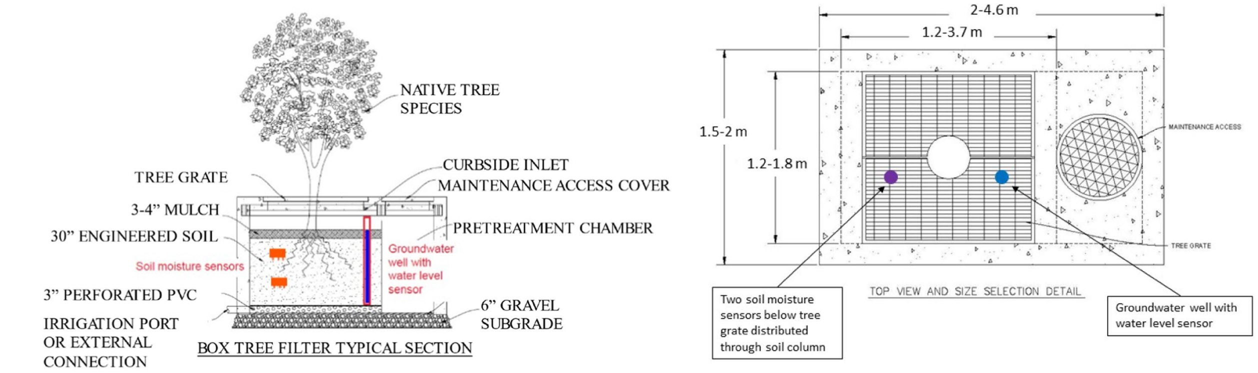

FIGURE 5
Instrumentation designs for box tree filter in a green streetscape including soil moisture sensors and a piezometer with a water level sensor. Box tree filter section and plan drawings provided by the Delta Institute (Eskin et al., 2021).

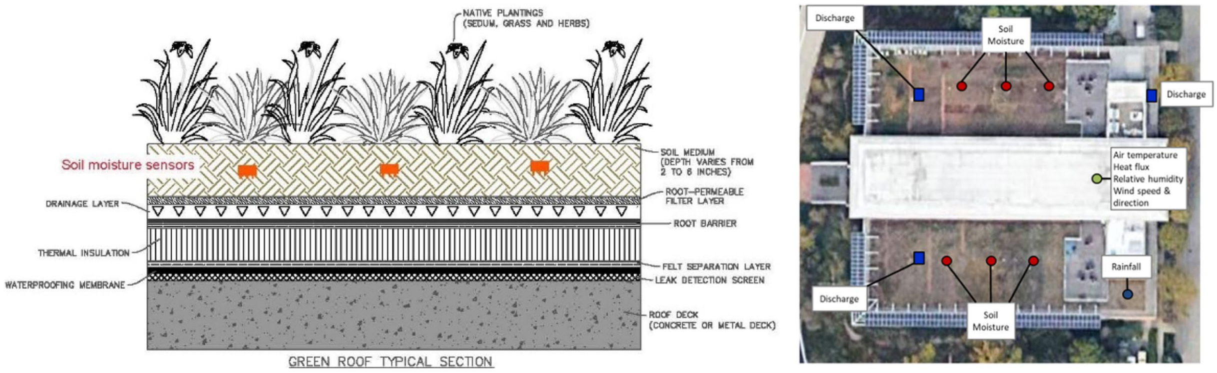

FIGURE 6
Instrumentation designs for green roof including soil moisture sensors. Instrumentation also includes a flow meter on the drainage outflow pipe. Green roof section drawing provided by the Delta Institute (Eskin et al., 2021).

this is a concern, we recommend installing one or more additional piezometers outside of bioretention basins and rain gardens to monitor the groundwater table. Both pre- and post-construction groundwater monitoring is recommended to understand the limitations imposed by the regional water table and the consequences of NBS on groundwater levels.

In a green streetscape (Figure 5), we recommend installing 1–3 soil moisture sensors distributed vertically through the soil column to measure subsurface stormwater storage within soil pore space (Grey et al., 2018). Where possible, we also recommend installing additional groundwater level sensors to measure the total subsurface water storage (Grey et al., 2018) and/or surface water flow sensors to measure the effects of tree plantings on stormwater discharge. In Table 1, sensor recommendations and cost estimates are provided for both streetscapes at the individual scale (e.g., one box tree filter) and at the city block scale (e.g., ten box tree filters). At the block scale not every box tree filter needs to be instrumented, and our cost estimates are based on instrumenting 50% of box tree filters.

Green roofs (Figure 6) are designed with a shallow substrate and provide storage in soil pore space, in addition to water uptake through plants. Soil moisture sensors are the main instrumentation required (Versini et al., 2016; Ouellet et al., 2021). In addition, many green roofs have outflow pipes that discharge excess water. Non-contact flow meters (i.e., ones that do not block stormwater drainage) or weirs with water level sensors to measure outflow provide useful information for conducting water balances and calculating water storage (Carson et al., 2013; Fassman-Beck et al., 2013; Ouellet et al., 2021).

In nature preserves (Figure 7), a combination of soil moisture sensors, piezometers, and water level sensors are recommended for determining site water balances and estimating hydrologic storage. Since surface-groundwater interactions are important in these systems, surface water level sensors should be used in concert with piezometers to capture both surface and groundwater storage (Gonzalez et al., 2023). Surface water flow measurements will often also be useful to measure discharge to urban waterways (e.g., streams, rivers, engineered drainage ditches) and downstream areas of the watershed. Placement of sensors within a large natural area is much more complex than in small-scale NBS, like a rain garden. Pre-installation modelling of site topography and flow paths is useful to determine hydrological connectivity to the surrounding urban hydrologic connections, such as natural streams and engineered stormwater conveyance ditches, and low points within the site, where

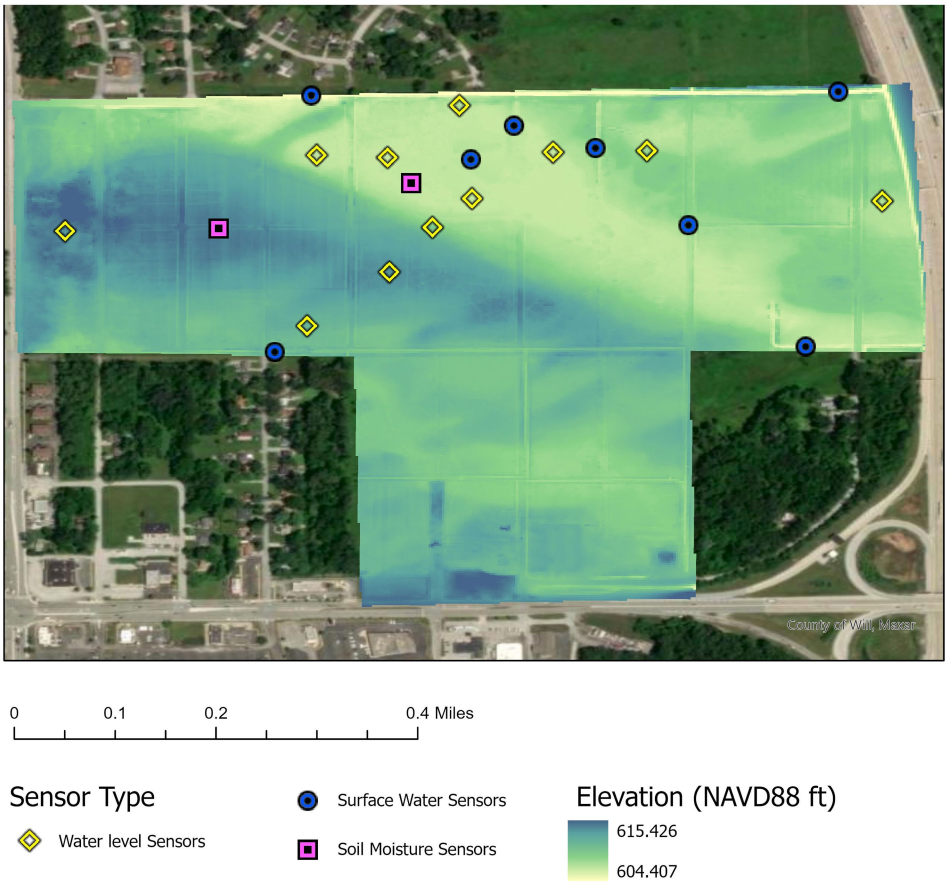

FIGURE 7
Sensor layout for large natural green space (Gensburg Markham Prairie in Markham, Illinois) including surface water level sensors, piezometers with groundwater level sensors and soil moisture sensors overlayed on a digital elevation model (DEM) derived from 2009 aerial LiDAR Survey (Cook County Board of Commissioners, 2010).

pooling of stormwater is anticipated. Local LiDAR data, which is frequently available for public use, and digital elevation models (DEMs) are useful to understand site drainage and inform the optimal placement of sensors to accurately monitor site water balance.

For community greenspaces embedded within highly urbanized areas (Figure 8), on-site piezometers are recommended for monitoring site water balances and stormwater storage (Xie et al., 2021). In addition, flow meters or weirs and water level sensors are useful to document the reduction of stormwater inflow into the urban drainage system (Jarden et al., 2016). In addition, the scale of community greenspaces and NBS often requires coordination between community-based monitoring and governmental infrastructure monitoring. This is an opportunity for community science measurements in collaboration between local residents and government agencies. This is particularly useful for long-term adaptive performance monitoring to inform maintenance. In addition, flow meters or weirs and water level sensors in surrounding drainage infrastructure, like stormwater catch basins, provide data on interactions between the site and drainage infrastructure and can be used to determine the reduction of inflow into the drainage system due to the storage provided by the community greenspace.

In addition to recommendations on the type and number of sensors needed to obtain site water balances, in Table 1 we provide cost estimates for instrumentation of community-centered NBS projects based on the desired data quality. Rain gauges should be located near NBS installations and can be shared by multiple NBS installations in

FIGURE 8
Sensor layout for community green space including groundwater level sensors and catch basin water level sensors. Figure shows aerial view and sensor locations at the Garfield Park Eco-Orchard site in Chicago, IL.

TABLE 1 Instrumentation designs and recommendations for six different classes of NBS.

Class of NBS	Scale	Degree of naturalness	Type and number of sensors	Cost estimate	References
Bioretention Basins Individual properties	5–100 m^2	Semi-Natural	2–4 soil moisture sensors 2 piezometers with water level sensors 1 surface water level sensor 1–2 flow meters or water level sensor and weir in inflow or outflow pipe	$8,000-20,000	Khan et al. (2012), Paus et al. (2015), Winston et al. (2016), Batalini de Macedo et al. (2019), Alizadehtazi and Montalto (2020), and Moruza et al. (2021)
Rain Gardens Individual properties	5–30 m^2	Semi-Natural	2–3 soil moisture sensors 2 piezometers with water level sensors 1 surface water level sensor	$5,000-15,000	Schlea et al. (2014), Mason et al. (2021), and Potter (2023)
Green Streetscapes Examples: Street trees, box tree filter, stormwater planter	1–10 m^2 (Individual)	Semi-Natural	1–3 soil moisture sensors 1 piezometer with water level sensor	$2,000-8,000	Grey et al. (2018) and Tu et al. (2020)
	10–100 m^2 (Block scale)		5–15 soil moisture sensors 5 piezometers with water level sensors	$10,000-40,000	
Green roofs Examples: extensive green roofs, intensive green roofs, rooftop gardens	25–2,000 m^2	Primarily Engineered	6–20 soil moisture sensors 1–3 flow meters or water level sensors and weirs	$5,000-30,000	Carson et al. (2013), Versini et al. (2016), and Ouellet et al. (2021)
Nature Preserves Examples: prairies, wetlands	1,500–450,000 m^2	Natural	Site specific. A combination of 8–20 surface water level sensors and/or piezometers with water level sensors 0–10 soil moisture sensors	$11,00-102,000	Hernandez Gonzalez et al. (2019) and Gonzalez et al. (2023)
Community Greenspaces Examples: community gardens, parks, playing fields	90–4,000 m^2	Semi-Natural	2–5 piezometers with water level sensors 2–3 water level sensors or flow meters in surrounding catch basins	$4,000-40,000	Xie et al. (2021)

Definitions of NBS classes are explained in the section above.

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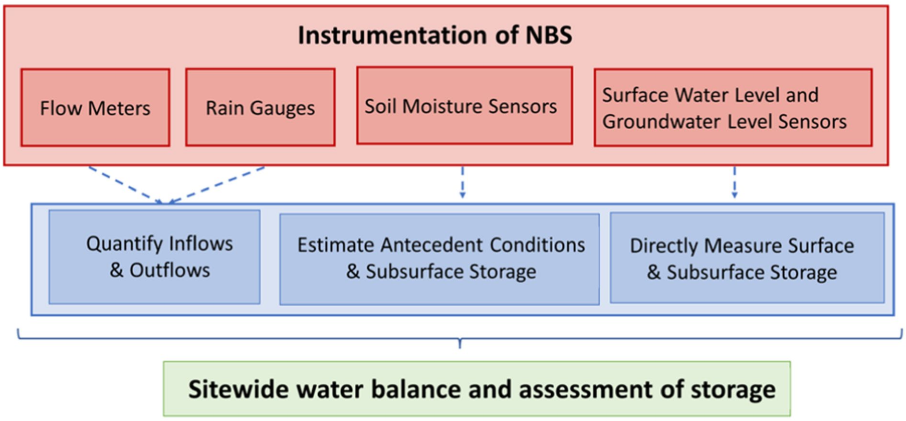

FIGURE 9
Conceptual framework for hydrological assessment of NBS performance.

close proximity to one another. Tipping bucket rain gauges costs range from $700 to $900. The lowest cost estimates in Table 1 are for a minimal monitoring strategy with the fewest recommended sensors at the lowest price per sensor, and the highest cost estimates are based on achieving the greatest spatial resolution (largest number of sensors) and data quality (highest price per sensor). The cost estimates are not comprehensive, but rather indicative for typical community-centered NBS projects conducted by non-profit organizations or local governmental agencies in the United States. Larger infrastructure projects and/or more challenging settings for instrument deployment are likely to require substantially larger investments.[1]

Data provided by the recommended instrumentation designs and monitoring methods is sufficient to conduct a water balance on NBS systems, which provides critical information on both ecohydrologic dynamics in greenspaces and the volume and timing of stormwater storage beyond retention and detention. This comprehensive monitoring approach allows for upscaling from individual site measurements to assess the impact of community-centered NBS on flooding and stormwater management at the catchment and regional scales. This approach is shown in the conceptual framework in Figure 9. Using water budget analysis, researchers can assess how NBS respond to different conditions such as climate, rainfall intensity or shallow groundwater tables (Zhang and Chui, 2019; Hung et al., 2020; Johnson et al., 2022). This can inform adaptive planning and selecting the most appropriate type of NBS for different settings (Kato and Ahern, 2008; Tang et al., 2020). The complexity of water budgets will vary based on the type of green infrastructure. The simplest example is a green roof, where the water input is limited to direct rainfall onto the roof, the hydrologic response time of the system is very short, and outflow can be directly measured at a discharge pipe. For this well-defined case, water mass balance can easily be obtained for a storm as $\Delta S = P - Q$, where S is volume of stormwater stored, P is the total precipitation volume, and Q is the total outflow obtained by integrating the measured discharge hydrograph over time (Versini et al., 2016). The complexity increases when calculating the water budget for a rain garden or bioswale, in which case there is stormwater input from both on-site rainfall and runoff from an off-site contributing area. In this case, we can directly measure the surface and groundwater storage and estimate short-term water balance based on the change in water level measured by surface and groundwater level sensors. In addition, flow meters can provide an estimate of outflow from the system (Fletcher et al., 2021). A longer-term water balance incorporating evapotranspiration and slow groundwater recharge can be estimated by incorporating modeling. However, because these systems respond quickly to precipitation a short-term water balance can provide an estimate of water storage based on direct measurements through the recommended suite of sensors and instrumentation. The complexity further increases in an embedded greenspace. If the system is relatively small and directly connected to a stormwater system, the same methods for rain gardens and bioswales can be used to measure storage and outflow. However, in systems with no clearly defined or engineered inlet or outlet, the total contributing area may vary between storms, making the inflow and outflow very challenging to measure. In these cases, some estimates of short-term storage can be obtained from direct measurements of changes in groundwater and surface water levels from sensors. However, on a larger time scale, modeling is often needed to better understand the longer-term dynamics. Many of the methods for this type of analysis are still under development, but the data provided by groundwater and surface water level measurements can provide a basis for estimating an overall water budget in these systems.

To determine the stormwater storage and other benefits provided by community-centered NBS, baseline data must also be collected for a significant period of time prior to NBS construction to provide points of comparison for a variety of storms of differing intensity, duration, and frequency. Pre-implementation monitoring is useful for both constructed NBS and related activities such as restoration of natural areas. Pre-implementation data collection can range from 3 months before construction begins (Jarden et al., 2016) to more than 2 years

1 The costs provided in Table 1 do not include personnel time for data collection, analysis, and sensor maintenance. The time requirements for these tasks can range from a minimum of approximately 70h annually to over 400h. This will vary based on the size and proximity of the site, the number and types of sensors at each site, and the extent of analysis required to meet project objectives and evaluate outcomes. Additional cost data are provided in Supplemental material.

(Boening-Ulman et al., 2022). The recommended duration of pre-implementation monitoring will vary based on local climate. Longer pre-implementation periods increase the diversity of storm conditions for comparison with post-installation performance. Our analysis of precipitation data in the Chicago region found that 1 year of pre-implementation data is needed to capture a variety of storm events and obtain a reasonable estimate of the precipitation distribution and site hydrological response (Griffin et al., 2020; Gonzalez et al., 2023). At a minimum, we recommend at least 3 months of pre-implementation data collected during the primary season of concern for high precipitation and flooding. Since sensors used for collecting baseline data can then be deployed within the NBS, no additional sensor costs are associated with collecting baseline data.

4 Discussion

4.1 Benefits and barriers of monitoring nature-based solutions performance

Monitoring NBS performance provides the information necessary to quantify the value of community-centered NBS for stormwater management and flood reduction, improve design, advocate for increased adoption of NBS, and inform the timing and type of maintenance needed (Ahern, 2007; Geberemariam, 2017; Gordon et al., 2018). Comparisons between pre-implementation and post-implementation monitoring data are important to quantify the additional stormwater storage provided by NBS and the resulting reduction in burden placed on the surface water drainage system (U.S. Geological Survey, 2023). These results can then be directly related to the benefits of NBS for reducing flooding in surrounding communities, and the corresponding economic value of these services. Quantitative data on the hydrological performance of NBS can also be used to advocate for additional investment in community-centered NBS from local water management authorities and municipalities. Tangible data are useful to local leaders in communicating the functionality and benefits of NBS to community members, who may not initially support or recognize the benefits of this type of infrastructure (Venkataramanan et al., 2020). In addition, when community members have access to and understand the data and can see the benefits of community-centered NBS, they can become advocates for these types of projects and provide incentives for their local representatives to provide additional support (Ando and Freitas, 2011; Lamond and Everett, 2019).

Long-term monitoring is critical to provide data on the long-term performance of NBS years after implementation and to inform maintenance needs; however, this often presents many challenges in terms of budget and staff availability (Wadzuk et al., 2021). Determining the minimum length of monitoring necessary to achieve project objectives, such as informing monitoring or quantifying the benefits of a community-centered NBS installation, should be discussed in the planning phase to allocate necessary staff time and financial resources. The most challenging aspects of long-term monitoring are deciding who should be responsible for long-term data collection and analysis, allocating staff time for this purpose, and securing budget for replacement of sensor hardware and parts. Municipalities are often understaffed, particularly in disadvantaged communities that are often more susceptible to flooding (Weller, 2023). Nonprofits and community organizations often experience the same challenges in terms of staffing. Therefore, allocating staff time and resources to long-term monitoring is often unfeasible unless resources are allocated as part of the primary NBS construction effort.

These challenges can be addressed through partnerships with local community members and by combining long-term monitoring efforts and maintenance projects. Monitoring data inform the type of maintenance required, which will in turn impact the long-term performance of the NBS (Wadzuk et al., 2021). Citizen science programs provide opportunities for community engagement and education while supporting long-term data collection for both research and operational purposes. Citizen science partnerships involve data collection, performance monitoring, and reporting by local volunteers, who have an incentive to see these sites perform well in the long term. NBS monitoring also presents the opportunity for workforce development (National Academies of Sciences, Engineering, and Medicine, 2018) and creating jobs for monitoring and maintenance of NBS in flood-prone communities. Beyond their value for both hydrologic research and operational performance monitoring, community science programs also provide value for public education and capacity building for maintenance and monitoring in environmental justice communities. These types of partnerships are particularly important for communities to improve climate resilience.

4.2 Data analysis

Data provided by the instrumentation of community-centered NBS will be used differently based on the goals and objectives of the institution or organization leading the monitoring. Municipalities and local non-profits or community organizations may be more interested in using data to inform the maintenance of their systems, whereas researchers may want to better understand how these systems function and inform the design of more efficient NBS.

Monitoring data are useful to inform ongoing operational maintenance, specifically when maintenance is needed and what type of maintenance is necessary. For example, Kazemi, 2014 used water level data to calculate infiltration rates and identify when clogging in a permeable pavement system had occurred. Similarly, the City of Lancaster, Pennsylvania used infiltration rates in permeable pavement to determine when vacuuming of these systems was needed and infiltration rates in bioswales to determine if additional soil testing or amendments were necessary (City of Lancaster, 2019). The early identification of maintenance needs can reduce costs over time, improve long-term performance of NBS, and help inform decision making for allocation of maintenance resources (Wadzuk et al., 2021).

Municipalities may also use monitoring data to track progress toward goals or toward meeting regulatory requirements. For example, the City of Philadelphia, Pennsylvania, uses monitoring data from NBS to assess how their program is reducing combined sewer overflows (CSOs) in the city and inform their long-term control plan for preventing CSOs (Philadelphia Water Department, 2009).

Lastly, monitoring data from multiple locations can be used to expand the assessment of NBS beyond the site scale to the catchment or regional scale. Scaling the analysis of NBS performance is critical to better understand the cumulative impacts on downstream hydrology, inform catchment management, and determine what factors impact changes in performance upon scaling (Golden and Hoghooghi, 2018). Monitoring can also inform community-centered NBS planning at the regional scale and inform decisions on the spatial configurations and network locations of NBS (Weber and Wolf, 2000; Golden and Hoghooghi, 2018; Shi and Qin, 2018; Goodspeed et al., 2022).

4.3 Community-centered impact assessment

Beyond monitoring the stormwater storage provided by community-centered NBS, there is a need for assessment of the actual impacts on community benefits, such as flood reduction and the improved experiences and perceptions of community members. Additional measurement methods are needed for this purpose beyond the instrumentation designs detailed above. One common means of measuring community impact and benefits is through surveys (Baptiste et al., 2015; Kim and Miller, 2019; Miller and Montalto, 2019; Anderson et al., 2021). However, low-income communities and communities of color may be frequently asked to take surveys on similar topics. Therefore, surveys should be prepared with input from community members and should not be unduly long or inaccessible to reduce the burden on community members.

Practitioners and researchers measuring impact should work with stakeholders to identify and prioritize outcome measures that address local concerns. In addition, an assessment of the risks of this type of survey data collection and analysis, including breach of confidentiality or data leaks (University of Oregon, Office of the Vice President for and Research and Innovation, n.d.), should be conducted at the beginning of the project in consultation with the community and relevant Institutional Review Boards, and all risks associated should be adequately communicated to the community beforehand. In cases where community members or community organizations are involved directly in impact assessments, whether recording visual observations or participating in surveys, the effort involved should be recognized and community members should be compensated fairly for their time.

Data management and privacy are concerns among community-centered NBS monitoring projects on both private and public property. Data management should be discussed as part of community engagement early in the planning process. At a minimum, data management, usage and privacy should be discussed with the community before sensors are installed and monitoring begins. Community members may have concerns about the use and protection of data collected near their homes, particularly imagery that may show individuals and the occurrence of flooding, which could impact local property values (Gourevitch et al., 2023). Efforts should be made to balance the protection and security of data with the availability of data for community and professional use. Practitioners engaged in monitoring should make every effort to provide a space for stakeholders to determine outcomes of data collection, including making data collected in communities available to community members in an accessible format. For research purposes, access should be provided to data in raw, processed, and analysed formats.

It is important to be aware of the historical context of data collection and research conduct in the neighborhood and community where monitoring will take place, especially for imagery. Over the past several decades, many local governments have expanded surveillance of public places with the stated goals of deterring crime and enforcing the law (Brown, 2008). However, throughout United States history, surveillance has been used as a means of enforcing structural racism, including enslavement, Jim Crow laws, and segregation, to the harm of millions of people of color (Gellman and Adler-Bell, 2017; Arnett, 2020; Lee and Chin, 2022). As a result, practitioners need to approach monitoring technology with surveillance implications through authentic, responsive engagement with community stakeholders and with an overarching mandate to avoid causing harm.

Community engagement is a key component of selecting the location, type, and scale of community-centered NBS in the area in which it is implemented. However, this is outside the scope of this paper and is discussed by Ferreira et al. (2020) and Mok et al. (2021).

5 Conclusion

Nature-based solutions are a promising technology for addressing urban stormwater management, an issue that will only become more critical in the face of climate change and urbanization. However, there is a need for more systematic collection of consistent performance data using similar monitoring methods. To address this gap, this paper provides a summary of available literature on commonly used methods for monitoring NBS and recommendations for consistent monitoring of community-centered NBS systems that vary in form, scale, and degree of naturalness. In addition, we provide an overview of how this monitoring data can be used to evaluate NBS performance and discuss common barriers to this type of monitoring. The application of the monitoring methodologies presented here would provide consistent performance data, which could be used to quantify the hydrological benefits of community-centered NBS and allow for regional comparisons of the performance of NBS systems. This would support greater adoption of the most appropriate NBS for stormwater management in different urban systems, thereby decreasing flooding and increasing adaptation to the impacts of climate change.

The recommendations presented here are particularly useful for community-based organizations and non-profit organizations who are now leading the planning and implementation of community-centered NBS systems in many areas, but previously had been provided limited resources for how to perform this type of monitoring. In addition, the recommendations presented are also applicable for research institutions analysing the performance of NBS, and government agencies, such as municipal park districts or water and sewer authorities. Cost estimates provided in this paper can be used to develop monitoring budgets, which should be included in the overall NBS project budget to ensure that adequate financial and staff resources are allocated for monitoring and maintenance efforts.

Author contributions

CO'B: Conceptualization, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. MM: Conceptualization, Visualization, Writing – original draft, Writing – review & editing. LC: Visualization, Writing – original draft, Writing – review & editing. JJ: Writing – original draft, Writing – review & editing. JW: Visualization, Writing – original draft, Writing – review & editing. RW: Conceptualization, Writing – original draft, Writing – review & editing. DW-C: Conceptualization, Writing – original draft, Writing – review & editing. AS: Writing

– original draft, Writing – review & editing. KR: Writing – original draft, Writing – review & editing. DG: Writing – original draft, Writing – review & editing. WM: Conceptualization, Supervision, Writing – original draft, Writing – review & editing. AP: Conceptualization, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

KR was employed by OAI, Inc. DG was employed by Waterwell, LLC.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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