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Framework for the documentation of nature-based solutions for stormwater management

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ABSTRACT

Nature-based solutions (NBSs) are widely implemented for stormwater management; as such they have become important assets that require proper asset management at different stages of their service life. Hence, there is a need for systematic documentation of the applied NBS in accordance with the principles of infrastructure asset management and in combination with a set of requirements in the newly adopted National Standard NS3456:2022 in Norway. A framework for the documentation of NBSs was developed based on a systematic literature study, the experience gained from operating NBS pilots, and the interaction with stakeholders in a research centre, Klima 2050. The framework proposed a set of specific information in the form of a data structure covering a set of categories that presents information gathered during the planning, design, operation, and maintenance phases of the NBS. Both technical and sociotechnical aspects were included in the data structure. The data structure can be tailor-made depending on the type of NBS applied. The data structure was applied in documenting the NBS pilots of the research centre to demonstrate the framework's ability to help ensure a smooth flow of information from the actors involved in the planning, constructing, and operating of the NBS.

Key words: asset management, data structure, framework for documentation, nature-based solutions

HIGHLIGHTS

- Application of infrastructure asset management principles in the implementation of NBS for stormwater management.
- Systematization of the data requirement for NBS planning, design, construction, and operation and maintenance based on literature and pilot studies.
- Formulation of a framework for documentation of NBSs.
- Suggestion for a data structure with an example of implementation in an NBS pilot.

INTRODUCTION

The concept of nature-based solutions (NBSs) has emerged as a key tool for solving various environmental and societal challenges. There are specific features for an intervention to be classified as a part of NBSs. NBSs use the features and processes of a natural complex system such as their ability to store carbon and regulate water flow to achieve desired outcomes, e.g., reduced disaster risk, improved human well-being and socially inclusive green growth. In addition, NBSs offer multiple co-benefits, an effective performance, and are economically efficient (Kõiv-Vainik *et al.* 2022; Sowińska-Świerkosz & García 2022; Su *et al.* 2023). Such an intervention concept has been implemented widely, including tackling the problems arising from the climate change and stormwater management (Li *et al.* 2019; Kõiv-Vainik *et al.* 2022). NBSs can be found in many forms and variations complicating the collection of information on their specifications. Various terminologies have been used in the literature to effectively describe the principles and practices of urban drainage, including the new/alternative approaches applied in stormwater management (Fletcher *et al.* 2015). The term 'nature-based solution' in this paper shall cover, but is not limited to, best management practices (BMPs), green infrastructure (GI), integrated urban water management (IUWM), low impact development (LID), low impact urban design and development (LIUDD), stormwater control measures (SCMs), and sustainable urban drainage systems (SUDS).

Over the last 15 years, the NBS has gained increasing attention as a stormwater management solution across the world. In Norway, this shift gained momentum, starting with the national guideline for stormwater management published in 2008 (Lindholm *et al.* 2008) which was the first to put the local stormwater management concept into an organized structure. The guideline introduced the three-step strategic approach to stormwater management: (i) small events should be infiltrated locally, (ii) medium events should be detained locally as much as possible, and (iii) large events must be handled through a safe flood approach. The blue paper published in 2015 emphasized again the beneficial use of open and local solutions to handle stormwater and proposed several changes in the national laws that regulate stormwater issues (NOU 2015:16). The first change put in action was noticed in the national guidelines for energy and adaptions to climate change that was effectuated by the Norwegian parliament in 2018 (Kommunal- og distriktsdepartementet 2018), stating that the NBS should be the default for stormwater management, if other solutions are to be used, they need to be justified. Recently, in March 2020, a few changes in the national plan and building act, pollution act, water and wastewater treatment act were proposed and sent for public consultation. The proposals will clarify the definitions and the responsibilities and strengthen how stormwater should preferably be handled in urban areas as well as how NBSs should be implemented. Hence, the use of the NBS is expected to gain a more pronounced role in city planning as well as the preferred solutions for private property developers in Norway. Norway has established a unique and long-term co-creation approach to climate risk mitigation manifested by the establishment of the public–private research partnership in *Klima 2050*. This initiative is a Norwegian, research-driven, innovation centre involving nine partners from industry, six from the public sector, and five from research and academic organizations. The collaboration has run for 8 years (2015–2023). The objective of *Klima 2050* is to reduce the societal risks associated with climate changes and enhanced precipitation (Lohne 2022). *Klima 2050* has used pilot projects as an instrument to facilitate co-creation, innovation, demonstration, and dissemination. One of the work packages in *Klima 2050* has focused on stormwater management, and several pilot projects related to innovative NBSs for stormwater management have been defined.

As an asset, the NBS should be managed properly right from the beginning of the planning, design, and construction process to the operation and maintenance phase, up to the end-of-life stage (Kõiv-Vainik *et al.* 2022). Managing NBSs require optimizing their performance. This creates a need to study the best ways to design and maintain them, starting from the identification of the main design parameters for selected solutions to be registered on a water utility inventory database, to identify the typical failure mode and influencing factors driving the planning of maintenance cycles, as well as to describe required maintenance operations for a variety of NBSs. Infrastructure Asset Management (IAM) has been applied for decades to support the management of aging grey infrastructure, and the methodologies applied can also inspire the management of GI. IAM models use information about the system's performance, changing structural conditions, O&M practices to guide and modify responses, routine activities, procedures, and capital investments to try to prevent and predict the occurrence of problems. Modelling performance requires observational data on past performance of similar facilities and understanding of the mechanisms of aging and failures contributing to the decline of performance over time. With varying access to such data in a structured way, the potential benefits of asset management are limited, both in the short- and long-term time horizons. Asset management is defined in the ISO 55000:2014 (International Organization for Standardization 2014) as 'coordinated activity of an organization to realize value from assets'. For infrastructure assets, IAM includes making the optimal decisions in the management of all physical assets through the entire life cycle. Effective asset management ensures that capital investments and maintenance expenditures are well targeted in the decisions on how much, where, when and how to maintain and/or rehabilitate the assets as individual components or as a system (e.g., pipeline networks). The decision must be based on technical, functional, and social-economic-environmental criteria. 'Performance assessment,' 'whole life costs analysis', and 'risk management' are the keywords in the context of IAM, also defined as 'the art of balancing performance, cost, and risk' (Brown & Humphrey 2005). Defining and applying these methodologies and approaches to the management of the NBS is a domain attracting the interest of the research community. However, IAM for the NBS is currently in an early stage and underdeveloped owing to a lack of monitoring techniques covering the broad range of NBS benefits and performance indicators, inspection techniques covering relevant failure mechanisms, and models describing these mechanisms. Unclear maintenance and rehabilitation options, and sufficient support tools to aid the stakeholders in the operation and maintenance of NBSs are also lacking (Langeveld *et al.* 2022). An extensive work still needs to be performed to support decision-making at all levels in which IAM is organized, i.e., strategic, tactical, and operational level, covering a range of aspects from long-term necessary investments down to technical decisions during construction (Alegre *et al.* 2016).

Research on maintenance of NBSs over the last 30 years addresses different challenges regarding maintenance and the loss of characteristics with inadequate level of maintenance (Lindsey *et al.* 1992; Brown & Hunt 2012; Blecken *et al.* 2017; de Macedo *et al.* 2017). Nevertheless, NBS projects are completed without necessary service contracts. In addition to the water quantity effects, the lack of service contracts poses a risk to the continuity of delivering the desired socio-economic and environmental benefits in the long term (Kabisch *et al.* 2016). As stakeholders recognize the problems with inadequate maintenance in NBS projects, the development of manuals and guidelines progresses. Even though the focus on utilizing NBSs to meet a variety of challenges is high and the number of nature-based instalments is expected to increase drastically in the years to come, several challenges for NBS implementation and adoption are still reported. A recent study that assessed many full-scale NBS instalments around the world reported a strong need for more decisive information about stormwater capabilities for many NBSs (Kõiv-Vainik *et al.* 2022). Another study that interviewed flood risk management expert communities identified a long range of barriers to implementation of the NBS largely related to unknown effects of NBS, locational decisions and institutional barriers (Raška *et al.* 2022). This is supported in a national study among Norwegian municipalities that pointed out that lack of performance data is a major showstopper for the NBS (Aanderaa *et al.* 2020). The study also identified other barriers for wider adoption of NBS including the lack of systems for interdisciplinary decision-making processes, land conflicts, uncertain operation, and maintenance procedures with associated costs. Recently, a framework for interdisciplinary planning process was proposed (Albert *et al.* 2021), but the other obstacles identified by Aanderaa *et al.* remain. Another barrier for wider NBS implementation is the perceived risk that follows all innovative technology and that leads to slow adoption of the NBS (Flyen *et al.* 2018; Hauge *et al.* 2019; Sarabi *et al.* 2020). This challenge may eventually be solved if the practical problems with implementation, operation and maintenance are kept to a minimum through a well-functioning asset management. This also includes a system for handling detailed information about where the NBS are located, how they should be operated and maintained and by whom. Furthermore, for NBS interventions that are part of a building, they must also comply with requirements applicable for buildings (Andenæs *et al.* 2018). One such national requirement is the 'Documentation for management, operation, maintenance and development of construction works' set by the Norwegian Standard (NS 3456:2022) that dictates the documentation requirements set for building. The standard requires notably specific documentation details of a building and hence also for the NBS. For example, the documentation must include a user manual, detailed description of the maintenance procedures and as-built technical drawings of the asset.

The objective of this paper is to identify and propose a data structure for documentation of the NBS in stormwater management that gives a unified approach for presenting, comparing and documenting the most vital information and characteristics of such solutions. To propose and specify such a data structure, the following questions were addressed: (i) What data framework, categories, or topics are recommended for NBS asset management? (ii) Are there any formal data requirements not covered from the current practice? (iii) How should the data be presented and used by practitioners?

MATERIALS AND METHODS

Systematic literature review

The literature review presented in this study is based on an established research methodology that ensures a comprehensive search process and systematic review of relevant literature (Booth *et al.* 2022). To make the aim of the study more concrete, the CIMO framework was used (Petticrew & Roberts 2006). Table 1 shows a specification of what the literature search should contain within each of the categories: *Context* (where), *Intervention* (what), *Mechanisms* (how), and *Outcome* (result). The search terms that were used within each of the categories are shown in Table 2, where the search terms between each category were linked together with *AND*, while search terms within each category were linked together with *OR* (not shown). The keywords were identified by studying the title, abstract and keywords of a small selection of articles and reports (Erickson *et al.* 2018; Mullaly 2018; Stormwater BMP Maintenance Task Committee 2019; Beryani *et al.* 2021). The results of literature

Table 1 | Concretization of literature search using the CIMO framework

Context	Documentation of nature-based solutions for stormwater management
Intervention	Unit process, unit operation, technical solution, concept of treatment, and nature-based solutions
Mechanisms	Design, operation, maintenance, asset management
Outcome	Guideline, regulation, requirement, decision support, design–operation–maintenance tool, and framework

Table 2 | Applied search words and Boolean operations used for the CIMO framework

Context (where)		Intervention (what)		Mechanisms (how)		Outcome (result)
Urban runoff	**AND**	SUDS	**AND**	Design	**AND**	Guideline
stormwater		Nature-based solutions		Operation		Data structure
		Decentralized system		Maintenance		Regulation
		Local treatment		Data		Decision support
		Source control		Information system		Data requirement
		Filtration		Inventory		Parameter
		Swales		Asset management		Framework
		Permeable pavement		Collection		Variable
		Green roof		Record		
		Grey roof		Rehabilitation		
		Bioretention		Planning		
		Low impact development		Sustainable development		
				Investment		

search were then subjected to four stages of screening with specific requirements imposed subsequently to the results from each stage as illustrated in Figure 1.

Innovative NBSs for stormwater management

Table 3 shows an overview of Klima 2050's pilot projects, including those owned by Klima 2050 partners and Figure 2 presents the photos of the pilot projects. The performance of these solutions is presented elsewhere (https://www.klima2050.no/ definition). The experience gained working with these pilot projects was used to supplement the findings from the literature. Suggestions and input to the needed data for NBS data structure have been gathered through *thematic meetings, workshops,* and *practical work* together with different stakeholders such as technology providers and solution owners within the Klima 2050 partnerships.

RESULTS AND DISCUSSION

Recommended data framework, categories, or topics for NBS asset management

The SCOPUS database was used in the study and the search was carried out on 22 August 2022. Table 4 shows an overview of the number of search hits (i.e., number of articles) from each screening stage. The first search yielded 1,165 hits when the search words in Table 2 were imposed to the search field of the database. These articles were then filtered based on the criteria set for Screening 1 and the search was narrowed down to articles published between the years 2017 and 2022. A total of 539 articles were selected to be processed in Screening 2. The exact numbers of word hits in the title and keywords were then counted and resulted in 489 articles for Screening 3 that were ranked and sorted as shown in Table 4.

As seen from Table 4, the 'heatmap' gives a good indication of the focus areas of these articles. With reference to the first research question focusing on the status of frameworks for the NBS documentation, Table 4 clearly shows that there are no available articles addressing this issue directly as indicated by the empty cells in the top rows of Mechanism (M) and Outcome (O) of the CIMO framework applied. The non-empty cells (i.e., cells with search word hits) were checked manually and, in fact, the topics discussed in these articles do not

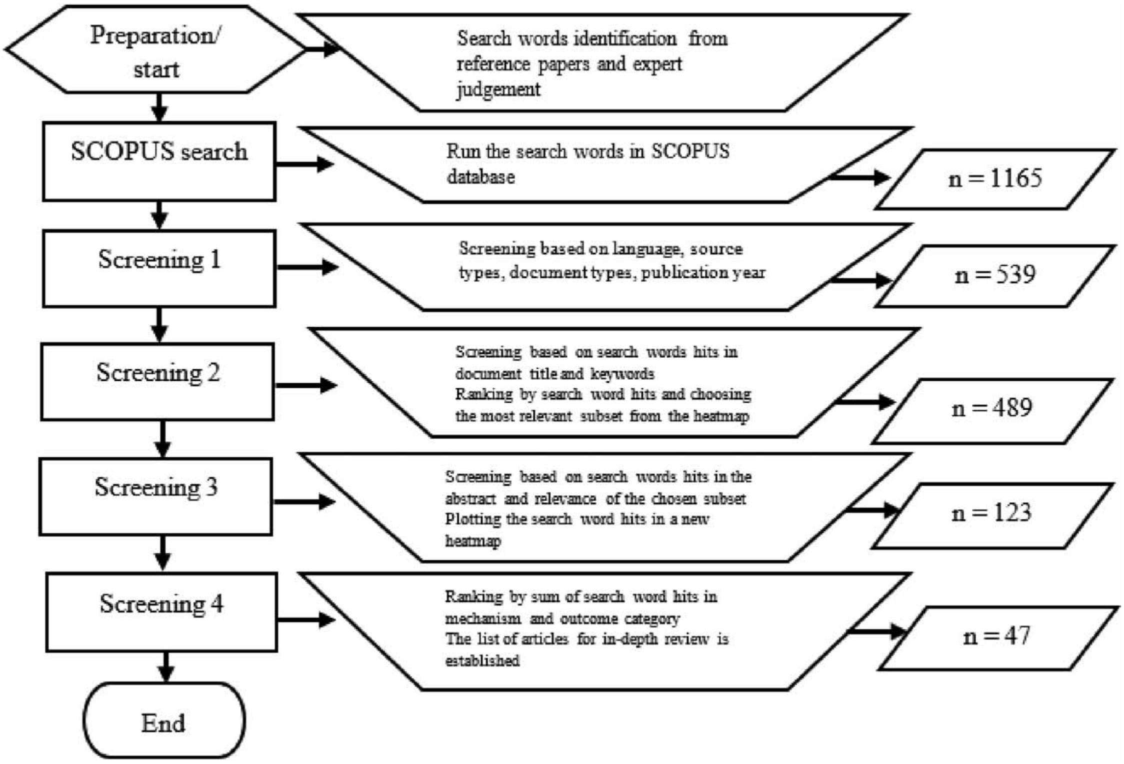

Figure 1 | Step-by-step screening process of the relevant articles from the search results.

Table 3 | Pilot projects organized by Klima 2050

Name	Owner	Solution(s)
Høvringen #1	Leca Saint-Gobain	Detention-based roof alternative 1 with sedum
Høvringen #2	Skjæveland Group AS	Detention-based roof alternative 2 with permeable pavements
Høvringen #3	Isola AS	Detention-based roof alternative 3 with sedum
Trondheim Town Square	Trondheim Municipality	Infiltration; detention
ZEB Laboratory	SINTEF and NTNU	Rain gardens; permeable pavement; detention basin
Rv 3 (motorway)	Statens Vegvesen	Grass swale
Fv 505 (highway)	Statens Vegvesen	Pre-sedimentation; sedimentation

precisely deal with the NBS documentation framework sought for. Hence, the answer to the first research question is a resounding no. However, the 489 screened articles indeed discuss some of the important aspects related to the NBS documentation as discussed in the following sections.

Search topics

As also seen from Table 4, the 'heatmap' delivers a good indication of the articles that include the search words and, interestingly, the number of articles with the return search word hits seem to be normally distributed if plotted based on their sum of search words hits (1–10). To limit the number of articles for the later investigation, the 10-search word hits groups were ranked simply by totalling the scores of each column. The numbers of articles with 4- and 5-search word hits (corresponding to 135 and 123 articles, respectively) were at the top of the list. The total search word counts of the 4- and 5-search word hit groups were 540 and 615, respectively, indicating that the 123 articles in the 5-search word hits group would likely fulfil the search criteria better. Hence, the articles in this group were chosen to be further examined. In Screening 4, the search words were matched against each other in the article's abstract that resulted in a new 'heatmap' plot as seen in Table 5. This enables a closer examination of the focus area/topic discussing the search words by their counterparts. In addition, the heatmap

Figure 2 | The pilot projects: Høvringen (left), ZEB Laboratory (middle), Riksvei (Rv) 3 (right, top), and Trondheim Town Square (right, bottom). Photos: Klima 2050.

also magnifies the 'gaps' in Table 4 indicated by the empty green cells in which the search returned zero results. By summation of the search word hits and leaving out the ones with such 'gaps', the final list of articles for in-depth review was established. In the end, a total of 47 articles were selected for the in-depth review.

Key aspects

The articles for the in-depth review highlight some important key aspects of NBSs that need documenting. Given that NBSs cover a wide spectrum of different solutions, the specific information of *the type of* the *NBS* being implemented needs to be identified. According to Ghodsi *et al.* (2020), who investigated stormwater management practices linked to the climate change, the applied NBSs need to fulfil a certain set of specific requirements, e.g., associated to the *location* and *expected performance* to meet water quality and quantity goals. Hence, description of the solution shall naturally be documented amply including the specific requirements for the NBS to perform its functions. Water quantity has been the main reason for applying NBSs in stormwater management in the changing climate. The same study reported that if the choice of location for an NBS is optimized, one can expect a significant runoff volume reduction from a certain area. In terms of expected performance to meet the water quality goals, there is a strong indication that NBSs can help with water quality improvement of some regulated pollutants. For example, Drapper & Hornbuckle (2018) monitored the performance of NBSs applied in urban stormwater runoff from a medium-density residential development to improve total suspended solids (TSS), total phosphorus (TP), and total nitrogen (TN) and Fang *et al.* (2021) investigated the biofilter outflow concentrations of heavy metals using a range of design and operational factors as input variables, both studies report positive impacts of the NBS application in water quality improvement of these regulated parameters.

Phases of activity

The literature covers a wide range of specific issues in different phase activities (i.e., planning, design, operation, and maintenance) of the NBS application in stormwater management. In the planning phase, one needs to consider the *choice and placement of* the *NBS* as the general considerations. Kaykhosravi *et al.* (2019) reiterate the importance of considering the working principles of the solutions (e.g., reducing the land slope, increasing perviousness, and/or providing storage volume) to control the flood risk and show that the degree of this control significantly depends on the location of the stormwater solutions within a catchment. Priority allocation of the solutions to the sites that contribute the most to runoff generation will help retrofit downstream locations to

Table 4 | Search words 'heatmap' based on the number of search word hits

489 articles		Search word hits									
Count of Search word hits		1	2	3	4	5	6	7	8	9	10
Number of articles		6	32	89	135	123	67	21	10	4	2
C	Sum of urban runoff	0	0	1	5	14	9	4	4	0	0
	Sum of stormwater	1	22	70	122	106	61	19	9	4	2
I	Sum of gray roof	0	0	0	0	0	0	0	0	0	0
	Sum of local treatment	0	0	0	0	0	0	0	0	0	0
	Sum of decentralised system	0	0	0	0	0	1	0	0	0	0
	Sum of source control	0	0	0	2	4	0	0	2	0	0
	Sum of nature-based solutions	1	0	1	7	6	7	0	1	1	0
	Sum of SUDS	0	2	3	11	11	4	5	0	1	0
	Sum of swales	0	0	5	9	10	6	5	2	1	1
	Sum of permeable pavement	0	1	4	5	13	20	4	4	3	2
	Sum of green roof	0	6	20	30	19	9	5	4	4	2
	Sum of low impact development	0	2	7	28	38	21	9	5	2	2
	Sum of bioretention	0	3	15	25	35	23	8	7	2	2
	Sum of filtration	1	4	17	22	55	33	11	6	3	1
M	Sum of data	0	0	0	0	0	0	0	0	0	0
	Sum of record	0	0	0	0	0	0	0	0	1	0
	Sum of asset management	0	0	0	0	0	0	1	0	0	0
	Sum of inventory	0	0	0	1	0	0	1	0	0	0
	Sum of information system	0	0	0	1	2	0	1	0	0	0
	Sum of rehabilitation	0	0	0	2	0	1	1	0	1	0
	Sum of sustainable development	0	0	2	1	2	3	0	1	0	1
	Sum of collection	0	1	1	5	2	2	3	0	0	0
	Sum of investment	0	0	1	6	1	6	1	2	0	1
	Sum of maintenance	0	1	7	7	23	15	11	4	2	0
	Sum of operation	0	0	7	17	22	15	9	3	2	1
	Sum of planning	0	3	6	20	26	25	5	5	2	1
	Sum of design	1	6	35	90	92	57	18	7	4	1
O	Sum of data structure	0	0	0	0	0	0	0	0	0	0
	Sum of data requirement	0	0	0	0	0	1	0	0	0	0
	Sum of decision support	0	1	1	4	1	4	1	0	1	0
	Sum of regulation	1	0	13	12	12	7	1	1	0	0
	Sum of guideline	0	0	8	13	17	15	4	2	2	0
	Sum of variable	0	2	10	23	23	12	8	3	0	0
	Sum of framework	1	1	9	32	27	15	5	5	0	1
	Sum of parameter	0	9	24	40	54	30	7	3	0	2

limit runoff generation effectively. Yao *et al.* (2020) suggest that the effect of the spatial location of the NBS on runoff mitigation was rainfall dependent. These findings provide insights into the hydrological role of the NBS and suggest that proper siting of NBS facilities should be a consideration for urban stormwater management to fulfil the hydrological efficiency and cost-effectiveness planning target. Moreover, Mani *et al.* (2019) underline that such correct decisions from the planning phase will also help minimize the implementation, maintenance costs, and the service-performance reduction of the stormwater solutions. Indeed, *decision-making* of NBS implementation may not necessarily be a straightforward process and often include multiple dimensions to consider as emphasized by BenDor *et al.* (2018) and Qiu *et al.* (2021), especially when dealing with planning of multiple NBS in a certain area. For example, Liang *et al.* (2020) developed a framework that comprises an extensive number of indicators, e.g., resilience, flood volume, flood duration time, hydraulic performance index, annual runoff, volume control, rainfall usage, pollution control, social acceptability, greenhouse gas emission, and cost. Meanwhile, Castro (2022) incorporates components of social equity and hydro-environmental performance in their decision-making framework. Nonetheless, there is a need for a holistic, yet practical framework for assessing the context-specific needs of decision-making, while considering the strengths, limitations, cost-effectiveness, climate scenario, and trade-offs of NBS application in urban stormwater management.

In the design phase, there is compelling evidence that design of the NBS shall incorporate a more dynamic approach that includes additional factors such as exfiltration and evapotranspiration to fulfil the *performance*

Table 5 | Search words 'heatmap' based on the chosen subset of search result (5-search words hits)

		C		I												M													O							
	123 articles	urban runoff	stormwater	gray roof	local treatment	decentralised system	source control	nature-based solutions	SUDS	swales	permeable pavement	green roof	low impact development	bioretention	filtration	data	record	asset management	inventory	information system	rehabilitation	sustainable development	collection	investment	maintenance	operation	planning	design	data structure	data requirement	decision support	regulation	guideline	variable	framework	parameter
C	urban runoff	14	11	0	0	0	1	2	0	1	0	1	3	2	6	0	0	0	0	0	0	1	0	0	1	1	2	10	0	0	1	1	2	3	2	5
	stormwater		106	0	0	0	4	5	9	6	10	12	32	26	46	0	0	0	0	2	0	1	2	1	21	21	21	81	0	0	1	9	16	19	24	44
I	gray roof			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	local treatment				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	decentralised system					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	source control						4	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	3	0	0	0	0	0	1	1	1
	nature-based solutions							6	0	0	0	0	0	0	3	0	0	0	0	0	0	1	0	0	1	0	3	2	0	0	0	0	2	1	2	2
	SUDS								11	2	2	2	1	1	5	0	0	0	0	1	0	0	0	0	2	1	3	6	0	0	0	1	2	2	2	2
	swales									10	1	2	2	2	8	0	0	0	0	0	0	0	0	0	1	0	0	7	0	0	0	0	0	1	2	4
	permeable pavement										13	4	3	1	6	0	0	0	0	0	0	0	0	0	2	1	2	8	0	0	0	3	1	1	2	5
	green roof											19	5	3	5	0	0	0	0	0	0	0	0	0	4	1	4	13	0	0	0	4	0	5	2	8
	low impact development												38	5	9	0	0	0	0	1	0	1	0	1	4	5	12	28	0	0	1	2	5	5	13	14
	bioretention													35	17	0	0	0	0	0	0	0	1	0	2	5	3	31	0	0	0	5	5	7	2	22
	filtration														55	0	0	0	0	0	0	1	1	0	10	10	3	38	0	0	0	2	6	8	8	28
M	data															0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	record																0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	asset management																	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	inventory																		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	information system																			2	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0
	rehabilitation																				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	sustainable development																					2	0	0	0	0	1	0	0	0	0	0	0	0	0	2
	collection																						2	0	0	0	1	1	0	0	0	0	0	0	0	1
	investment																							1	1	1	0	0	0	0	0	0	0	0	0	0
	maintenance																								23	8	3	11	0	0	0	2	5	2	6	6
	operation																									22	5	11	0	0	0	1	3	4	3	6
	planning																										26	14	0	0	0	3	5	5	6	7
	design																											92	0	0	1	8	11	18	21	43
O	data structure																												0	0	0	0	0	0	0	0
	data requirement																													0	0	0	0	0	0	0
	decision support																														1	0	0	0	0	0
	regulation																															12	0	2	0	5
	guideline																																17	1	3	1
	variable																																	23	2	5
	framework																																		27	5
	parameter																																			54

*requirement*s. This was evident from a study conducted by Traver & Ebrahimian (2017) that shows the customary practice of crediting water volume based on soil and surface storage undervalues the performance potential of an NBS. Indeed, the local conditions, materials and construction practice may also impose additional or specific requirements as to how the NBS design should look, e.g., owing to the specific climate conditions and the aim for the NBS to be multifunctional as implied by Tahvonen (2018), to be applicable at different locations and hydrological conditions as underlined by Weaver & Nachabe (2019) and Zhang & Chui (2017), to cover other specific purposes such as renovation of old urban tissues as described by Saadatpour *et al.* (2020), and to implement an innovative stormwater management approach such as that highlighted by Zhang *et al.* (2018) or the NBS material types as studied by Dai *et al.* (2022).

The trend of the NBS design is also moving towards encompassing not solely water quantity issues, but also *water quality* as an additional requirement. Interestingly, these two requirements can be complementary as suggested by Chin (2017) in a study that employed a set of governing equations for designing bioretention areas for both flood control and water quality control. It is proven that the NBS sized for water-quality control can also meet flood control regulations. In addition, Tahvonen (2018) and Tirpak *et al.* (2022) emphasize the importance of factors affecting the plant growth and their inner workings (i.e., plant–water relation) for specific NBS employing vegetation implying that the NBS may assert *specific design requirements* depending on the NBS types implemented. In addition, care must also be taken in the construction process of the NBS. One important additional requirement for the NBS design can be related to the adaptability of the NBS to cope with the future climate scenario and uncertainties. As stressed by Yu *et al.* (2022), this aspect should be incorporated early in the planning and design phase. Apart for the technical requirement, there is of course a need to consider the *cost element* as pointed out by Qiu *et al.* (2021) and Latifi *et al.* (2019). Cost-effectiveness shall be considered in the design and implementation of the NBS in stormwater management.

Co-benefits

The *co-benefit effects* of NBS application on the biodiversity are often overlooked. Joyner *et al.* (2019) presented very interesting results from their study of five different types of green infrastructures (vegetated swales, right of way bioswales (ROWB), including street-side infiltration systems and enhanced tree pits, and an urban forest).

The study reveals that these green infrastructures can promote biodiversity, especially in the case of ROWB, by influencing the soil parameters (particularly organic matter) and the bacterial community. Multifunctionality of NBS, i.e., water quantity, water quality, biodiversity challenges, amenity, and recreational co-benefits, is an inherent feature of the NBS that is often untapped (Lähde *et al.* 2019; Latifi *et al.* 2019), including the potential for stakeholders' involvement (Stein *et al.* 2017; Torres *et al.* 2020) and positive effects on human well-being (Rai *et al.* 2019). This reiterates the need for an interdisciplinary approach that combines ecological comprehension and the system thinking into the NBS design connected with the wider social ecological framework of urban landscape. Adaptability of the NBS to future challenges in terms of climate and urbanization can also be utilized as a performance indicator of the NBS. Spatial distribution of the NBS in urban settings and water balance components, e.g., runoff volume, evapotranspiration, groundwater recharge/storage change, can help model the performance of the current NBS settings and identify if further intervention or retrofitting is needed (Pappalardo *et al.* 2017; Leimgruber *et al.* 2018; Wang *et al.* 2019; Le Floch *et al.* 2022). Many of these benefits and co-benefits are certainly of great interest for the stakeholders but are often not directly quantifiable or easily communicated.

Attempts have been made to bridge this shortcoming, for example a framework developed by Watkin *et al.* (2019) to assess the NBS's benefits and co-benefits based on certain steps, i.e., defining benefit categories, setting up indicators with stakeholders' involvement, calculating indicators values, grading of NBS, and proposing recommendations to strengthen NBS implementation. Given the trend of NBS applications in stormwater management, it opens doors to many opportunities such as the creation of new occupations, business prospects, and research areas for the innovative solutions to the stormwater problematics to take place (Radcliffe 2018).

Operation and maintenance

Operation and maintenance of the NBS have been the focus of several articles emphasizing the need to keep the performance, functionality, and effectiveness of NBSs as intended by their design and to cope with the ever-changing climate variables. Hence, there is a need for a way to check the performance status of the NBS so that the need for maintenance interventions can be predicted by means of certain *operational variables/parameters*. There is an extensive number of performance indicators of the NBS in the literature addressing various performance aspects. Given that the main goal of the NBS application in stormwater management is aimed towards *water quantity*, this aspect is well covered by the literature and can be dependent on the type of the NBS applied. Runoff reduction, peak flow reduction/delay, and water retention capacity are some of the most common performance indicators measured for the NBS (Bettella *et al.* 2018; Xu *et al.* 2019). Heavy metals removal (Fang *et al.* 2021), microorganisms (Shen *et al.* 2020; Graham *et al.* 2021; Jitolis *et al.* 2021), micropollutants (Luthy *et al.* 2019), and nutrients (Sparkman *et al.* 2017) have been a strong focus of *water quality* aspect investigated in the literature that dictate the potential reuse of the stormwater, e.g., for irrigation, bathing water, and toilet flushing, but certainly not for potable use yet unless the key operational and design variables are optimized, and a clear regulatory framework is set (Luthy *et al.* 2019).

Mobilia *et al.* (2021), for example, studied the climate and design variables of a green roof in relation to its performance and were able to conclude that soil moisture can be a good predictor for retention capacity of a green roof both under moderate and severe rainfall. Involvement of sensors for collecting data and monitoring the NBS performance can help set up a cost-effective supervising process of the NBS performance, for example as studied by Ali *et al.* (2020). Such an approach is beneficial for NBS systems that change over time. For example, the fact that the long-term performance of a bioretention system can be affected by the interactions between media and the living components of the system, i.e., vegetation as argued by Skorobogatov *et al.* (2021) that eventually affect the infiltration, storage capacity, and treatment performance of a bioretention system. A well-performed *periodic/regular maintenance* can prolong the lifetime and performance of the NBS as highlighted by Drapper & Hornbuckle (2018). However, specific actions/measures/information for operation and maintenance of the NBS are mostly missing in the literature.

Formal data requirements not covered from the current practice

During the work with the pilot projects in Klima 2050 (see Table 3), the need for a common data structure describing the NBS has crystallized from the discussions with the many different involved stakeholders, such as land and building owners, manufacturers, constructors, consultants and municipalities. Many of the data topics/issues discussed with the stakeholders are shared with those discussed in the literature, hence, there is a need to identify topics that are not addressed in the literature but come from the experience with a new NBS. Also discussed among the stakeholders within the different pilot projects is how should the *data be* *managed*. Especially when the solutions include some sort of instrumentation, the data management should be clarified in an early phase of the project development and a plan for handling the data in an operational phase should be planned for. Another topic that was frequently discussed with the stakeholders in the different pilot projects is where to find *useful information* about the solution. It seems beneficial to also incorporate *additional references* covering useful information available from external sources.

For outdoor solutions as part of a new building or construction areas, the solutions will have the same requirement for documentation as the building itself. In Norway, the documentation needed to be approved follows the National Standard NS3456:2022 'Documentation for management, operation, maintenance and development of construction works'. This means that the NBS should also be documented according to this standard. Comparing the required topics from the standard with the topics discussed in the literature, the following topics requested by the standard are missing; *user's manual*, *periodic inspection,* and a*s-built documentation*. The as-built documentation includes several mandatory formal topics, namely (i) *approval*, (ii) *protocol* (iii) *identification*, (iv) *technical drawings*, and (v) *documentation or pictures*. All these topics should be covered by the data structure in order to be in accordance with the abovementioned standard.

Suggested data framework for the NBS documentation

Combining the findings from the literature and extracting experience from the co-creation process in the Klima 2050 pilot projects, the proposed framework of the NBS documentation is given in Table 6. The proposed data structure consists of seven main categories covering aspects to document, e.g., necessary basic information, phase activities (planning, design, operation, and maintenance), compliance with the regulatory framework, and additional documents/references that may support implementation and operation of the NBS. As seen in the table, the aspects covered/discussed in the literature are marked with the referenced articles and the ones that are not marked in boldface and discussed in the preceding section of this article. There is a need for specifying the main categories more thoroughly as a step-by-step guide to populate the table. This would allow the users to know exactly what is required as data input under each category. The full table can be read in Supplementary Material A including the description of the specific information targeted by the data structure.

The data structure also adopts an important aspect that must be documented according to the National Standard NS3456:2022 'as-built' (point 6 in Table 6). As-built consists of some specific documentations from approval of the construction and performance of the NBS to record keeping of the technical drawings and protocol/records of actions done to the NBS. For the partners in Klima 2050 pilot projects, it is in their interest to document the technical data and the points addressed in the regulatory work in one data structure. This is arguably an advantage to put all related information about the solution in one place, and is generic, i.e., not only applicable for Norway, but also for others who wish to implement the data structure.

Examples of use

The suggested framework and the resulting data structure were tested on the pilot solutions described in Table 3. An example from one of Klima 2050 pilots, the Høvringen #1, a detention-based roof with associated layers is presented in Supplementary Material B. As seen in the example, not all fields are considered relevant to the solution or the project owner, and some data may be missing. For example, the following codes *n.a.* (not applicable) and *m* (missing) were used if the data are not relevant and for missing data, respectively. The data structure was continuously updated at the different stages of its lifetime from information provided by different stakeholders contributing to the establishment of the pilot. This was a coordinated effort led by one of the project's partners.

The solutions at Høvringen were constructed for research purposes, hence some of the information provided may not be useful for an average solution owner. The technical, performance, and maintenance data are presented amply in the data structure, however, a few points can be highlighted to illustrate what type of information may be collected and documented (refer to the table in Supplementary Material B):

- 1 Basic design (Sections 1.4 General description of the asset/3.3 Specific design requirements): It is important to clarify available dimensions and any physical restrictions as well as a list of the main components of the solution. In the Høvringen case, the available area allows construction of three plots with a dimension of 8 m by 11 m each. It is also shown that the roof's load bearing capacity is high and more than sufficient for blue-green solutions. Further, this solution was planned with sedum vegetation and an extra layer for expanded lightweight crushed clay aggregate (see Figure 2, left photo, green roof).

Table 6 | The proposed framework of the NBS documentation that highlights the aspects extracted from the literature and the missing ones (indicated with bold text)

Chapter	Main category	Sub-category	Reference
1	Basic information	1.1 Name of the NBS asset	
		1.2 Location	
		1.3 Type	Ghodsi *et al.* (2020)
		1.4 General description of the asset	Drapper & Hornbuckle (2018), Fang *et al.* (2021)
2	Planning	2.1 General considerations	BenDor *et al.* (2018), Liang *et al.* (2020), Qiu *et al.* (2021), Castro (2022)
		2.2 Placement/allocation	Kaykhosravi *et al.* (2019), Mani *et al.* (2019), Yao *et al.* (2020)
		2.3 Expected performance	Ghodsi *et al.* (2020)
3	Design	3.1 Water quantity	Traver & Ebrahimian (2017), Zhang & Chui (2017), Tahvonen (2018), Zhang *et al.* (2018), Weaver & Nachabe (2019), Saadatpour *et al.* (2020), Dai *et al.* (2022)
		3.2 Water quality	Chin (2017)
		3.3 Specific design requirements	Tahvonen (2018), Tirpak *et al.* (2022)
		3.4 Co-benefits	Stein *et al.* (2017), Joyner *et al.* (2019), Latifi *et al.* (2019), Lähde *et al.* (2019), Rai *et al.* (2019), Torres *et al.* (2020)
		3.5 Cost elements	Latifi *et al.* (2019), Qiu *et al.* (2021)
		3.6 Sensors	Ali *et al.* (2020), Mobilia *et al.* (2021), Skorobogatov *et al.* (2021)
		3.7 Data management	
4	Operation	**4.1 User's manual**	
		4.2 Periodic inspection	
5	Maintenance	5.1 Periodic maintenance	Drapper & Hornbuckle (2018)
		5.2 Rehabilitation/ modification need	Pappalardo *et al.* (2017), Leimgruber *et al.* (2018), Wang *et al.* (2019), Le Floch *et al.* (2022)
6	As-built	6.1 Performance evaluation	Sparkman *et al.* (2017), Bettella *et al.* (2018), Radcliffe (2018), Luthy *et al.* (2019), Watkin *et al.* (2019), Xu *et al.* (2019), Shen *et al.* (2020), Fang *et al.* (2021), Graham *et al.* (2021), Jitolis *et al.* (2021)
		6.2 Approval	
		6.3 Protocols/records	
		6.4 Identification	
		6.5 Technical drawings	
		6.6 Documentation/ picture	
7	Additional references	**7.1 Useful information/ reference**	

- 2 Planning: It is important to assess potential risks and how the solutions should interact with existing systems. In our case we had easy access to the existing municipal sewage system and there was also an existing overflow system we could connect to. Hence, the risk for flooding was assessed to be small. Further, based on local restriction, we had to establish our own path to access the roof to avoid conflict with another part of the roof that was not subject to renovation.
- 3 Design: It is to clarify the main purpose of the solution and to give detailed information an its expected performance. Høvringen solutions were constructed for detention of stormwater so Section 3.1 Water quantity is quite detailed, whereas Sections 3.2 Water quality and 3.4 Co-benefits are described in much less detail.
- 3 Design: The pilot is well equipped to monitor the performance of the solutions as detailed in Sections 3.6 Sensors and 3.7 Data management. The equipment was planned quite early in the project and described in detail. Acquisition and installation of sensors, loggers and visualization of data features became an extensive task in the project.
- 4 Operation: Operational actions and responsibilities were clarified and documented in Section 4.2 Periodic inspection. In our case, it was the building owner (the municipality) that was appointed responsible for following up the solutions on-site.

- 5 Maintenance: The maintenance actions and responsibilities were clarified and documented in Section 5.1 Periodic maintenance.
- 6 As-built: It provides links to online monitoring (live picture feed, weather information, and flow data) and related scientific publications of the pilot.

Recommendations

The table is extensive and it can be inconvenient for the users to meticulously fill in every category. It can be argued that the table can be 'tailor-made' at the user/stakeholder level. For example, a decision maker would be interested in more overarching information provided in the table and how this information would help make the right decision. In contrast, an operator would like to find out specific actions pertaining to operation and/or maintenance measures to be implemented in specific cases and time to ensure the functionality of the NBS. In another case, the authority may like to have the ability to check if the solution in place complies with the relevant regulation they set, so on and so forth. Hence, there is a need to approach the table based on the users/stakeholders' point of view. In addition, the data structure can also be expanded by tackling different interventions implemented in one location. The fact that the data structure can be viewed as *a living document*, filling in the table should not pose an issue. As the construction of the NBS may involve different actors responsible for various stages of the construction, the responsibility of filling in the table can be divided and passed on from one party to another as the construction stage proceeds. For example, from an NBS owner to a consultant who hands over the approved design to a constructor, and the finished installation will then be handed over back to the owner. The owner would later refer to the manuals and protocols of proper operation and maintenance of the solution and would continue to follow the guidelines given. During the service life of the solution, the owner can opt to hire a company for any major maintenance or rehabilitation needed, again referring to the living document and keeping the record updated. Hence, not only does the data structure serve as a living document, but it also keeps a proper key *information flow* should it need reviewing at the later stages of the NBS service.

Technical vs. sociotechnical aspects

As evident from the process of establishing the data structure, involvement of the stakeholders is important. Hence, the data structure covers not only the technical aspects of the NBS, e.g., hardware and software needed to operate the NBS, but also the sociotechnical ones such as the importance of stakeholders' involvement and delegation of roles and responsibilities to ensure a well-functioning NBS installation.

The importance of the human factor in the management of the NBS cannot be overstated. The technical aspects can only do so much without the input of human contribution. Operating the hardware and software, taking decisions based on the data and implementing solutions is the contribution of the human workforce, thus showing the importance of the seamless integration of technical and sociotechnical aspects for this system to function in a real-world environment. User-driven data gathering ensures covering the requirements of multiple actors or players, with different values and preferences. In addition, it will help the selection of NBS measures, by comparing the costs but also the benefits foreseen by the different actors for alternative options.

A recent study in Klima 2050 underlines that a greater understanding of public perceptions and priorities is needed to build support for the NBS implementation (Thodesen *et al.* 2022). The study presented a way of understanding public expectations and what aspects of the project correlated with public acceptance or resistance through interviews with the municipality and stakeholders. A set of different co-benefits was identified, e.g., environmental, child-related activities, maintenance of the NBS and funding. As seen in Table 3, such aspects are covered by the proposed framework and, hence, the framework should help provide decision-makers greater insight into public priorities.

Implications and challenges

Implementation of the data structure shall benefit the implementation of the NBS for stormwater management by applying the principle of IAM at strategic, tactical, and operational levels, where each one of them has specific purposes. The data structure reflects information about the system performance, changing structural conditions, operation and maintenance practices that will contribute to guide and modify responses, routines activities, procedures, and to try to prevent and predict the occurrence of problems. The research presented here mainly aims to offer support on a tactical and operational level, which refers to the planning and implementing of maintenance interventions. In this direction, to define the functional requirements of the NBS is a pre-requisite to drive data collection. The data structure will also help decide and communicate distribution of responsibilities among the stakeholders. Furthermore, the data structure presents a standardized format of information that allows easy comparison of different solutions and minimizes the risk of misunderstanding between the actors.

As the amount of data about different kinds of NBS is more broadly available, through many years of gathering, such data can be used for modelling purposes. Data give possibilities for understanding the systems and their development over time, especially if the data are applied in different kinds of modelling. Over time, the proposed framework will enable the users to predict long-term rehabilitation and investment needs on a strategic level. Hence, the framework will support all levels of asset management and will aid sustainable development by optimizing both short-term and long-term measures and interventions.

The principle of *technical approval* in the National Standard NS3456:2022, adopted in the data structure, may pose challenges for the technology providers in documenting the performance and benefits that their solution may provide. To do so they would need third party actors to give them the necessary certifications which may require long tests and qualification procedures. Nevertheless, the certification of the NBS really is a fair trade-off given that the point of departure of this work is to implement the principles of IAM. The issue is, there is no organization/entity that can perform such a service today, at least not in Norway. Such an institutional problem is one of the major barriers for the NBS uptake identified by Sarabi *et al.* (2020). Policy makers and authorities can offer incentives for such a business model to facilitate a solution to the barrier and to not further hamper uptake of the NBS.

Scope for future adaptations

We believe that the proposed framework will be sufficiently flexible to tackle new types of solutions and requirements as well as updated information over time. A simple flowchart has been made to illustrate the flexibility of the data structure as depicted in Supplementary Material C.

The fact that the NBS can take on different forms and shapes raises an obvious issue as to how such interventions can be approved let alone standardized. In addition, new NBSs will emerge as well as hybrid solutions combining traditional 'grey' solutions with NBSs bringing new and other levels of complexities. This is covered by the data structure that includes some 'solution-specific requirements/parameters' that can be tailor-made depending on the system in question.

Furthermore, the NBSs' performance can vary over time and, consequently, the way they should be operated or maintained would need adjustments. Therefore, future adaptations of the data structure should also take into account these factors. At the current stage of the data structure implementation in Klima 2050, this issue has not yet arisen, but we are confident that such factors can also be documented within the same data structure by version control (e.g., by adding new columns if a spreadsheet is used). This will ensure the continuity of the flow of information and the record-keeping of the NBS.

The most efficient use of the framework will be to incorporate it in an interactive tool, possibly linked to the geographical location. In the future, if the framework is implemented on a spatial map, the policymakers/municipalities will get a better understanding of which areas exert a high spatial coverage of solutions and less risk of stormwater issues versus those with fewer solutions implemented and are, therefore, of higher risk for stormwater issues. Research has already started in this direction with the aim to structure the requirements of a system for registration of information and data from literature in a comprehensive interactive map, where data are linked to different user-profiles and categorized within types of decisions levels (strategic, tactical, and operational) and multiple potential needs for data use. From the interactive maps, a list of minimum requirements for registration of the new NBS was developed as a proposal to design a national digital portal for documentation of NBSs (Fredriksen 2021). The Municipality of Oslo has the ambition to boost implementation of NBSs by aiming to build 2,030 NBS installations by 2030 as stated in their action plan for the city (Municipality of Oslo 2022). This would create a great opportunity to implement, test and improve the data framework proposed in this study and, moreover, to support the effort of implementing IAM principles in the NBS application.

CONCLUSION

This study proposes a framework for documentation of NBSs. The framework was developed by combining results from a systematic literature research, experience gained in the Klima 2050 centre from operating NBS pilots and through interaction with the stakeholders, and a set of requirements dictated at the national level.

A comprehensive data structure was developed specifying the information that is important to safeguard the implementation of the NBS based on the principles of the IAM at the tactical and operational level. A data structure that presents a set of specific information in different categories covering information gathered during the planning, design, operation, and maintenance phases of the NBS was proposed. The data structure encompasses the technical aspects of the NBS such as the hardware and software needed for its operation. Additionally, it also includes the sociotechnical aspects, such as the importance of stakeholders' involvement and the delegation of roles and responsibilities to ensure a well-functioning installation of the NBS. Given that the NBS come in many forms and shapes, the data structure was made flexible allowing later adjustments and/or modifications depending on the NBS system at hand. The data structure was then applied in documenting NBS pilots in the Klima 2050 project and was demonstrated to help ensure smooth flow of information from the actors involved in the establishment of the NBS. The data structure can serve as a living document providing the key information at the different phases of the NBS.

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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