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A Nature-based solution selection framework: criteria and processes for addressing hydro-meteorological hazards at open-air laboratories across Europe

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Abstract

Nature-based solutions (NbS) can be beneficial to help human communities build resilience to climate change by managing and mitigating related hydro-meteorological hazards (HMHs). Substantial research has been carried out in the past on the detection and assessment of HMHs and their derived risks. Yet, knowledge on the performance and functioning of NbS to address these hazards is severely lacking. The latter is exacerbated by the lack of practical and viable approaches that would help identify and select NbS for specific problems. The EU-funded OPERANDUM project established seven Open-Air Laboratories (OALs) across Europe to co-develop, test, and generate an evidence base from innovative NbS deployed to address HMHs such as flooding, droughts, landslides, erosion, and eutrophication. Herein, we detail the original approaches that each OAL followed in the process of identifying and selecting NbS for specific hazards with the aim of proposing a novel, generic framework for selecting NbS. We found that the process of selecting NBS was overall complex and context-specific in all the OALs, and it comprised 26 steps distributed across three stages: (i) Problem recognition, (ii) NbS identification, and (iii) NbS selection. We also identified over 20 selection criteria which, in most cases, were shared across OALs and were chiefly related to sustainability aspects. All the identified NbS were related to the regulation of the water cycle, and they were mostly chosen according to three main factors: (i) hazard type, (ii) hazard scale, and (iii) OAL size. We noticed that OALs exposed to landslides and erosion selected NbS capable to manage water budgets within the soil compartment at the local or landscape scale, while OALs exposed to floods, droughts, and eutrophication selected approaches to managing water transport and storage at the catchment scale. We successfully portrayed a synthesis of the stages and steps followed in the OALs' NbS selection process in a framework. The framework, which reflects the experiences of the stakeholders involved, is inclusive and integrated, and it can serve as a basis to inform NbS selection processes whilst facilitating the organisation of diverse stakeholders working towards finding solutions to natural hazards. We animate the future development of the proposed framework by integrating financial viability steps. We also encourage studies looking into the implementation of the proposed framework through quantitative approaches integrating multi-criteria analyses.

Keywords: Green infrastructure; Ecosystem-based management; Stakeholder participation; Co-creation; Ecological Engineering

1. INTRODUCTION

Nature-based solutions (NbS) are globally recognised for their potential to address societal and environmental challenges including biodiversity loss, climate change adaptation, and disaster risk reduction. NbS is an umbrella term for ecosystem-based approaches seeking the restoration, protection, sustainable management, and creation of ecosystems to build ecological and social resilience (e.g., IUCN, 2020a; EC, 2021). In Europe, NbS are valued and financed as a step towards a sustainable and resilient future in the context of regional frameworks such as the European Green Deal, the EU Biodiversity Strategy for 2030, and the EU Adaptation Strategy (EU, 2019, 2020, 2021). In contrast to conventional engineering solutions, NbS are supported by multiple stakeholders due to their co-benefits for the environment but, also, for the role NbS play in global frameworks supporting society and economy such as the Sustainable Development Goals (SDGs) and the targets of the Convention for Biological Diversity (CBD) (UN, 1992, 2015). Based on their features, ecosystem processes in which they are based, and combinations, NbS can be grouped into four main types: (i) blue (water-based approach), (ii) green (vegetation-based approach), (iii) mixed (green-blue), and (iv) hybrid (green/blue-grey) (Debele et al., 2019). In spite of their typology, NbS are especially important for helping human communities build resilience to climate change by managing and mitigating related hydro-meteorological hazards (HMHs) (e.g., Debele et al., 2019; Kumar et al., 2020).

HMHs are the subgroup of natural hazards that originate from the interaction of atmospheric, hydrological, or oceanographic processes, which can cause severe socio-economic disturbance and the loss of lives, services, livelihoods, properties, and environmental integrity (UNISDR, 2009; Kumar et al., 2020). Hydro-meteorological events comprising floods, droughts, hurricanes, tornadoes, heatwaves, storm surges, and landslides are dominant hazards in Europe, and they cause about 81% of deaths and 75% of economic losses, respectively (Debele et al., 2019). In this context, the EU-funded OPERANDUM project (www.operandum-project.eu) established seven Open-Air Laboratories (OALs) across Europe to co-develop, test, and generate an evidence base on innovative NbS against HMHs such as flooding, storm surges, landslides, erosion, and eutrophication.

OALs are a novel approach grounded in the 'living lab' concept for people-centred methodologies that prototype and test innovations in rural areas (Astorga et al., 2010). In the OPERANDUM project, the OALs aim at implementing NbS and at monitoring their effectiveness at a small scale, while a strong focus is set on fostering citizen and stakeholder participation throughout the life cycle of the NbS. This NbS co-design approach can facilitate the adoption of new NbS by local authorities and practitioners by establishing strong synergies between multiple actors. The OALs can also set the basis for creating new knowledge on the implementation of NbS, which should provide valuable insights into NbS replication and upscaling. Currently, the main challenge for implementing and upscaling NbS is the lack of long-term evidence on the feasibility and performance of NbS projects together with the lack of action-oriented frameworks contributing towards capacity building in NbS (Wickenberg et al., 2021). These frameworks should provide guidance for the design, implementation, and monitoring of NbS (Gonzalez-Ollauri et al., 2021; Mickovski et al., 2022). However, a key practical challenge for NbS planning is the selection of suitable and context-specific NbS for achieving strategic goals (Raymond et al., 2017; Cohen-Shacham et al., 2019).

The selection of NbS suiting the requirements, scale, and context of an intervention is not straightforward and it needs a specific skillset and expertise. To this end, a number of frameworks and approaches focusing on different aspects of the NbS selection process have been proposed in the scientific literature (e.g., Raymond et al., 2017; Alves et al., 2018; Pagano et al., 2019; Albert et al., 2021; Croeser et al., 2021). However, the majority of frameworks still require a practical application for validation since they have been developed in light of the evidence provided in the literature (e.g., Raymond et al., 2017 Calliari et al., 2019) and not on the basis of practical experience (e.g., Albert et al., 2021; Gonzalez-Ollauri et al., 2021). Hence, NbS selection processes implemented in real case studies, such as those taking place at the OPERANDUM's OALs, can provide useful learning points supporting NbS selection elsewhere. Yet, each OAL was established in a different environmental and socio-economic context, resulting in multiple, eclectic NbS selection processes that need to be merged into a framework first to be of use to other researchers and practitioners. The latter process is challenging, and it requires a sound, holistic understanding of NbS planning. In this paper, we strived to merge the multiple selection processes followed at the OALs, which did not explicitly follow an established approach (e.g., the IUCN Global Standard for NbS; IUCN, 2020a,b), into one single NbS selection framework.

Frameworks specifically built for selecting NbS are uncommon in the literature (e.g., Albert et al., 2021). However, there are several NbS frameworks from which information on NbS selection can be drawn (e.g., Liquete et al., 2016; Raymond et al., 2017; Calliari et al., 2019; Albert et al., 2021; Gomez Martin et al., 2020; Ruangpan et al., 2021; Sowińska-Świerkosz and García, 2021; Gonzalez-Ollauri et al., 2021). These frameworks generally establish step-wise selection approaches. Although the number of steps varies from framework to framework, there is a number of common steps - e.g., problem identification, creation of scenarios, development of solution strategies, and assessment of alternatives - with special emphasis on engaging stakeholders in the selection process wherever possible. The integration of stakeholders, including 'host communities', for NbS selection is highlighted in both principles for NbS calling for "broad participation" (Cohen-Shacham et al., 2016, 2019) and encouraging the incorporation of co-design, co-development, co-creation, and co-management processes into the NbS selection process to both increase benefits and produce knowledge (i.e., criteria for NbS outlined in the IUCN's 'Global Standard' for NbS report; IUCN, 2020a. But also see Frantzeskaki, 2019; Giordano et al., 2020; Puskás et al., 2021; Zingraff-Hamed et al., 2020). However, in practice, participatory approaches in NbS projects have mostly 'consulted' or 'informed' participants rather than transferring significant decision-making power (Puskas et al. 2021). Additionally, greater levels of participation are not always appropriate, and the selection of options may necessarily be constrained by a range of cultural, economic, political, and geographic factors (Wamsler et al. 2019; van der Vegt, 2018).

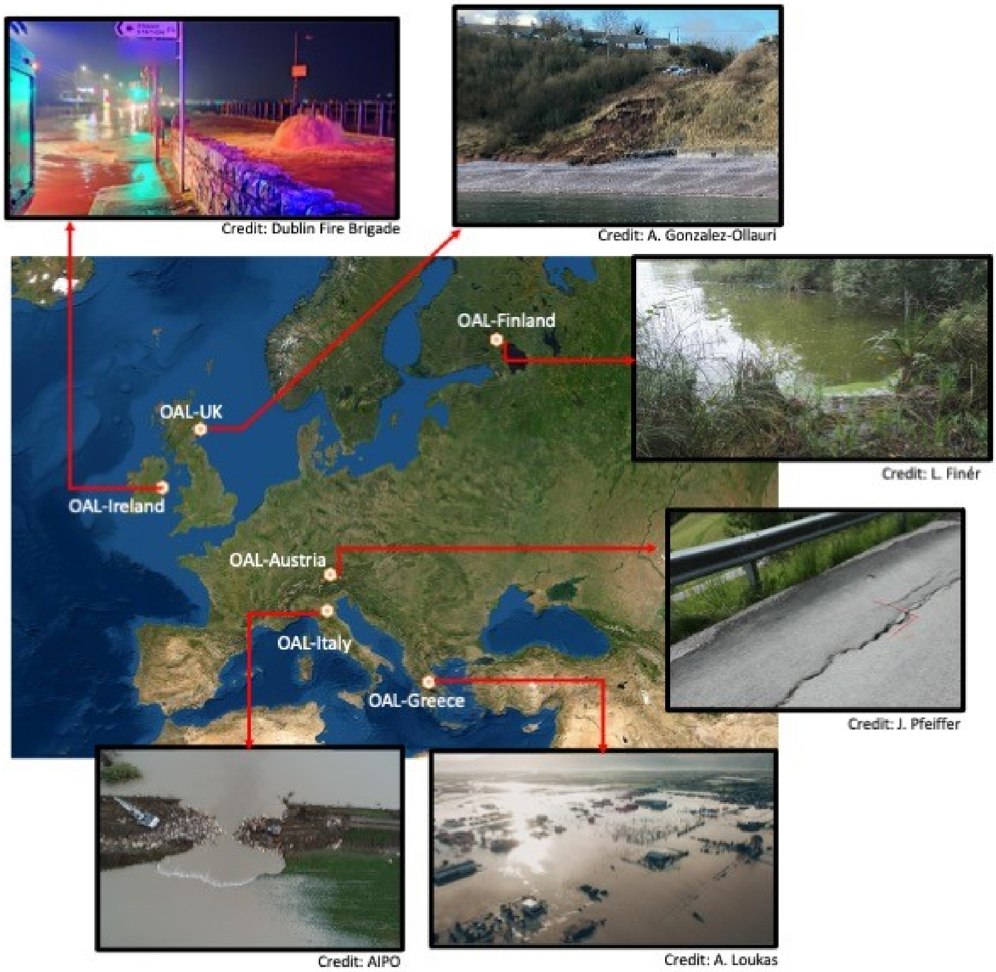
Overall, the existing NbS frameworks agree that NbS should be ultimately selected based on their performance against a hazard or for addressing other societal challenge(s) (e.g., Cohen-Shacham et al., 2016) under multiple scenarios of climate change. However, as empirical evidence on NbS performance is lacking, numerical modelling is commonly utilised as "expected evidence" to support the selection process (e.g., Albert et al., 2021). Most frameworks strive to shortlist few NbS alternatives which can then be rated against multiple criteria through participatory approaches (e.g., Raymond et al., 2017; Pagano et al., 2019) and multi-criteria analysis methods (e.g., Liquete et al., 2016; Alves et al., 2018; Croeser et al., 2021, Ruangpan et al., 2021). Common criteria are related to ecosystem services, co-benefits and trade-offs provision, costs, and stakeholders' perceptions (Liquete et al., 2016; Raymond et al., 2017; Ruangpan et al. 2021; Balzan et al., 2021; Ommer et al., 2022). However, it is essential to characterise the local setting to identify the problem correctly and select NbS accordingly (e.g., Albert et al., 2021; Gonzalez-Ollauri et al., 2021). This may include ensuring funding, considering applicable legislations and policies, or understanding the enablers, expectations, and barriers of stakeholders' involvement (e.g., Croeser et al., 2021; Sowińska-Świerkosz and García, 2021) together with a deep characterisation of the ecological, engineering, and socio-economic features of the site (e.g., Gonzalez-Ollauri et al., 2021).

The aim of this paper is to provide an original framework for selecting NbS against HMHs. This framework stems from the practical experience collected at six open-air laboratories distributed across Europe and exposed to different HMHs, ranging from landslides to eutrophication, and from floods to droughts. This paper is structured as follows: in the first Section, we introduce the methodology that we followed to map the NbS selection process at the OALs, and we provide the main features of the OALs in which this paper is framed. Then, we present a synthesis of the main steps and criteria followed by each OAL for selecting specific NbS, emphasising the similarities and differences across the OALs to then showcase a common NbS selection framework which can be widely used in the NbS selection process. We eventually discuss our findings against the wider body of literature, and we highlight the practical aspects of our study to inform the selection process in NbS planning projects.

2. METHODOLOGY

2.1. Open-air laboratories and hydro-meteorological hazards

We investigated the NbS selection process at six open-air laboratories (OALs) distributed across Europe (Fig. 1). The size of the OALs considered in this study ranged from few hectares to hundreds of square kilometres, covering a variety of scales that went from the slope and landscape scale (e.g., UK, Italy, and Austria) to the catchment scale (e.g., Greece and Finland); see Supplementary Material. Most of the OALs were established in rural areas with the exception of OAL-Ireland, which was set in the city of Dublin. The main ecosystem types found across the OALs were fluvial, lacustrine, forest, mountain, and coastal. The OALs were spread across different climate groups (Supplementary Material – Table S1; Köppen, 1884), which ranged from Subarctic and Alpine to Temperate Oceanic and Mediterranean. Overall, five different hydro-meteorological hazards (HMHs) were addressed with different NbS at the OALs – i.e., shallow landslides, deep-seated landslides, floods, droughts, and eutrophication – yet the main drivers for the HMHs were, in general, prolonged rainfall (or the lack of it), rapid snowmelt, and land use change (Fig. 2 and Table S1).



Credit: Dublin Fire Brigade

Credit: A. Gonzalez-Ollauri

Credit: L. Finér

Credit: J. Pfeiffer

Credit: AIPO

Credit: A. Loukas

Figure 1. Location of the Open-air labs (OAL) across Europe. Base map source: ESRI satellite.

In OAL-UK, located adjacent to Catterline Bay, Scotland, shallow landslide and coastal erosion are interlinked and occur simultaneously. The main causes of these HMHs are heavy and prolonged rainfall, surface water accumulation, and sea-level rise (Gonzalez-Ollauri and Mickovski, 2017a,b,c; Walvin and Mickovski, 2015), which are all predicted to increase in the UK due to climate change (IPCC, 2021). In OAL-Italy, riverbank failure and accumulation of earth deposits in the riverbed leads to overtopping events on the river Panaro in the Emilia-Romagna region, resulting in the frequent inundation of land and properties. As the frequency of floods is predicted to increase for the site, riverbank failure and overtopping will likely be more ubiquitous. OAL-Austria is subjected to a repeatedly accelerating deep-seated landslide in the Tuxer mountain range in the province of Tyrol. Using hydro-meteorological variables such as precipitations, snowmelt, and evapotranspiration, Pfeiffer et al. (2021) found that acceleration phases of the landslide were triggered either by infiltrating, prolonged rainfall, snowmelt, or both. Probable subsurface recharge areas were further assessed by exploiting a combined stable isotope and geo-statistical approach (Pfeiffer et al., 2022). The Dodder River catchment (OAL-Ireland) is exposed to floods derived from storm surges, tidal flooding, and rapid surface runoff leading to flash floods at the downstream part of the catchment. In OAL-

Greece, located along the Spercheios River, the river flow often exceeds the channel capacity, leading to frequent flood events. Heavy rainfall episodes together with land use changes (e.g., decrease in forest surface) are worsening the issue in OAL-Greece. However, the site is also subjected to severe droughts, as there is an increasing trend of months without rainfall. In OAL-Finland, located in the Lake Puruvesi, increasing loads of nutrients and sediment in surface runoff led to eutrophication of the oligotrophic waters of the lake. Climate change could increase winter runoff and shorten the snow cover period (Huttunen et al., 2015), thus increasing both nutrient and sediment loading in the lake. A range of risks are faced by the OALs as a result of the above-mentioned HMHs, which could result in damage to human life, property, and infrastructure, damage to environmental integrity and food production, and disruption of recreation and related business activities. More detailed information for each OAL is shown in Supplementary Material (Table S1).

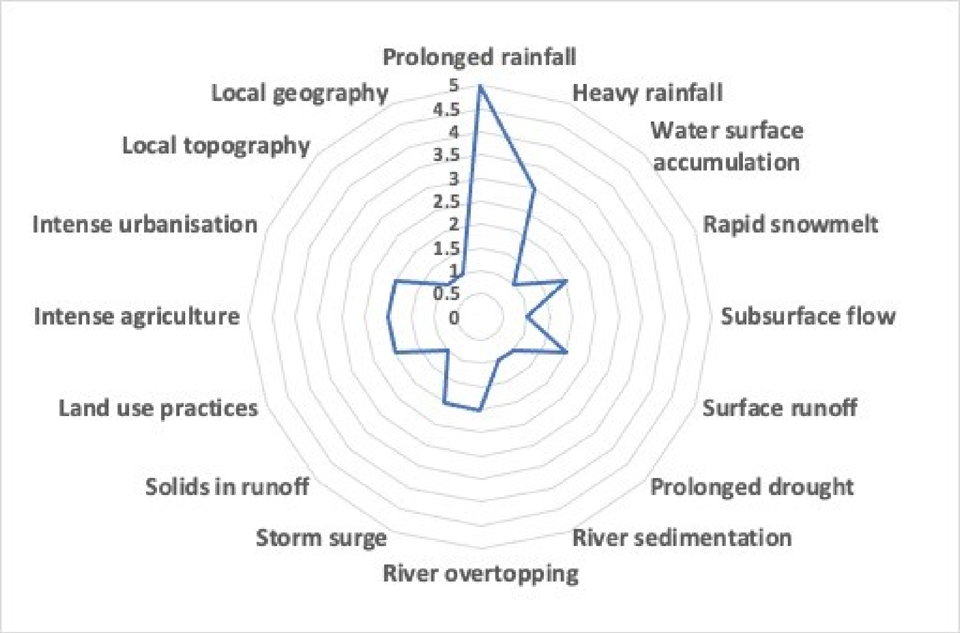


Figure 2. Spider chart showing the main drivers of HMHs at the OALs. Values 0 to 6 indicate the number of OALs reporting a particular driver of HMHs. For more detail, see Appendix A.

2.2. Mapping of the NbS selection process

We mapped the NbS selection process at six OALs distributed across Europe and exposed to different HMHs (Fig. 1 and Supplementary Material – Table S1) by asking the following three questions:

- How was the HMH problem recognised at the OAL?
- Which steps were followed for shortlisting NbS?
- Which NbS were selected and which selection criteria were considered?

The three questions were answered by representatives of each OAL through four online focus group discussions (FGD) held using MS Teams. One representative per OAL was requested to give a presentation addressing the questions followed by an open discussion and Q&As (questions and answers) between the participants. Two OALs presented at each FGD session. The participants had a direct relationship to one of the OALs and were academics and/or researchers from the institutions involved in the OPERANDUM project. The OAL representatives, who were appointed at the proposal stage of the project by the participating institutions involved in the OALs, were academic experts co-ordinating the research, stakeholder engagement, and NbS co-creation activities at each OAL. The Q&As and discussion, which emerged when the answers to the 3 above-mentioned questions were unclear or incomplete in the presentation, were led and moderated by the OAL representatives from Finland and the UK, who also led a Work Package on the operationalisation of the OALs within OPERANDUM. Using the information presented by the OAL representatives, we identified the key stakeholders involved in the NbS selection process at each OAL (Fig. 3). In addition, we draw the NbS selection criteria reported by the OALs into a table and a diagram (Table 1 and Figure 3), in which we mapped which OALs followed which criteria, and we identified the overall NbS types chosen by the OALs (Fig. 5 and Table 2). Following the FGDs, the OAL representatives were asked to illustrate their answers into arrow-box diagrams in which the steps of the NbS selection process were clearly identified and interconnected (see Supplementary Material). The answers provided by each OAL representative were then collated into a summary table (Supplementary Material – Table S2) which, together with the arrow-box diagrams, enabled us to map the overall NbS selection process in the form of an integrated flowchart or framework (Fig. 6). The latter integrates a synthesis of the actions and tasks undertaken by the pool of OALs in the process of selecting NbS.

In the following Section, we present a summary of the main findings stemming from the FGDs. The findings are chiefly focused on the process followed from the recognition of the problem to the selection of the NbS by the different OALs. We then portray in an integrated framework the common steps followed in the NbS selection process by the OALs, and we discuss the framework's features and usefulness against the existing literature on NbS selection.

3. RESULTS & DISCUSSION

The process of selecting NbS was overall complex and context-specific in all the OALs, it comprised more than 10 steps in every OAL (Fig. 6 and Table 3; Supplementary Material – Table S2), and it did not follow any established approaches such as the IUCN's Global Standard for NbS (IUCN, 2020a,b). However, the steps leading to the selection of NbS can be grouped into 3 main stages: (i) problem recognition, (ii) solutions identification, and (iii) NbS selection (Fig. 6; Table 3). A distinction was made herein between identification –i.e., the action of finding a potential NbS for a given site or context, and selection, i.e., the action of choosing an NbS as being the best or most suitable. Problem recognition was defined herein as the process of characterising the drivers, the nature, the location, the extent, and the derived consequences of a given hydro-meteorological hazard.

3.1. Problem recognition

The problem was in all cases readily identifiable, as the scale of the hazards was spatially perceptible (see Section 2.1). In most cases, the problem was first flagged by members of the communities living within or adjacent to the OAL, or by "user" groups benefiting from the OAL either for recreational or commercial purposes. This was generally followed by the appraisal of academic experts and local authorities. In other instances, the local authorities, or related agencies, raised awareness about the problem. The problem recognition phase sometimes led to the self-organisation of primary stakeholders into action groups or partnerships, which helped coordinate actions and seek resources against the identified hazards

(Section 2.1). In some cases, the emergence of action groups facilitated the inclusion of academic experts and practitioners (e.g., UK). In others, the experts were actively involved in the creation of action groups (e.g., Finland) (Figure 3; Supplementary Material – Table S2).

The problem recognition phase also involved activities oriented to gain insights and understanding into the context and into the HMHs. However, site investigation differed across the OALs, with some OALs reporting data-rich fieldwork campaigns characterising the socio-ecological context of the site (e.g., stakeholder surveys; measurement of HMHs variables/drivers), while others reported merely observational approaches (e.g., water colour and turbidity as a proxy for eutrophication; site visits to assess the location, size, and nature of landslides; Supplementary Material – Table S2). The investigation of the HMHs enabled the OALs to identify and gain understanding of the HMH drivers. In fact, the latter was a key step in the process of identifying solutions, as the solutions should, in most cases, be aimed at addressing the HMH drivers (Fig. 4). In all OALs, HMH investigation consisted in the analysis of past hazard events, which were often recalled and recorded by community members and were then corroborated with articles in news archives and databases (e.g., BGS National Landslide Database; BGS, 2022). The HMH events were subsequently compared against the relevant existing meteorological records to understand the severity and recurrence of the HMHs. One OAL carried out additional field surveys targeting the dynamics of the hazard and its drivers (i.e., OAL-Austria used terrestrial laser scanning to assess landslide displacements and monitored groundwater dynamics) while most employed computer-based, numerical models to understand the exposure of the OAL to the hazard (e.g., Gonzalez-Ollauri and Mickovski, 2017a; Gonzalez-Ollauri et al., 2021b; Spyrou et al., 2021). Site investigation and hazard analysis within the problem recognition stage was in all cases supported by consultation within an initial group of stakeholders. The latter generally comprised communities exposed to the HMHs, local authorities and related departments, and academic experts (Fig. 3). The consultations helped identify feasible solutions and, in some cases, to target specific areas for intervention (Table S2).

3.2. Identification of solutions

The identification of potential solutions to the diverse problems (i.e., HMHs) faced by the OALs generally begun by connecting with more stakeholders and by devising a co-creation strategy (e.g., Nunes et al., 2021). The latter aimed at opening up a participatory consultation process between stakeholders to find feasible, effective, and acceptable solutions for every OAL. To this end, stakeholders were mapped out at each OAL by the academic experts with support from the initial group of stakeholders established during the problem recognition phase (Fig. 4). Snowballing sampling approaches were commonly utilised to enhance the outreach capacity and to expand the list of stakeholders. Once the stakeholders were mapped out, they were grouped into primary (e.g., local residents, academic experts), secondary (e.g., other OAL users, practitioners, providers of technology), and tertiary (e.g., local authorities, OAL users, other suppliers) stakeholders. This classification helped with optimising engagement, communication, and input collection through the co-creation process, as not all stakeholder groups were involved in all stages of the consultation and decision process. The decision process mainly involved primary and secondary stakeholders. Overall, the stakeholders and their involvement in the co-creation process was different across OALs (Supplementary Material – Tables S1 and S2). In four OALs, local communities and end-users had a greater representation (i.e., UK, Austria Greece, Finland) while, in the other two (i.e., Italy and Ireland), local or regional authorities and associated agencies were more involved in problemsolving. Engagement with expert practitioners and/or technology providers was also common in most of the OALs (e.g., UK, Austria, Ireland, Italy) (Fig. 4).

Figure 3. Spider diagram showing the stakeholders involved in the NBS selection process. Values 0 to 6 indicate the number of OALs in which a particular stakeholder group was involved in NBS selection.

The co-creation process, which was iterative and normally comprised a series of informal discussions between academic experts and other stakeholder groups, FGDs, and workshops in a relaxed environment, was intended to establish selection criteria (Fig. 4; Table 1) and to shortlist NbS for implementation in each OAL (Fig. 5; Table 2). The co-creation process differed across OALs in terms of the utilised tools and approaches (Supplementary Material – Table S2). Some OALs employed elaborated approaches to retrieve input from the stakeholders, such as mind mapping (e.g., OAL-Finland) and citizen science methods (e.g., OAL-Ireland). These approaches helped to illustrate how the key actors envisioned the potential solutions. In other cases, however, the co-creation process was led by the experts who, following pertinent critical review of the available literature on existing, potential solutions, discussed options with the stakeholders and then gathered information on their perception and preference. The latter approach, which was generally conducted through semi-structured questionnaires and tailored FGDs (e.g., OAL-UK, Anderson et al., 2021, 2022), informed the construction of selection criteria lists (Table 1; Fig. 4). Site visits with the stakeholders and, in some cases, further site investigation, was also common across the OALs. Site visits were deemed essential (i) to build trust between the stakeholders, (ii) to envision the solutions, (iii) to identify opportunity spaces for NbS implementation, (iv) to gauge the feasibility of potential NbS, and (v) to build upon the list of NbS selection criteria (Tables 1 and 3).

Each OAL had to address HMHs differently, which not only depended on the size and nature of the OAL and the hazard, but also on the stakeholders involved. The NbS selection criteria reported by the six OALs were diverse and context-specific (Table 1 and Fig. 4), and they emerged from the discussions and consultations held between stakeholders during the co-creation process. Though the criteria were not established considering existing NbS frameworks (e.g., IUCN, 2020a), there was a high degree of commonality between OALs (Fig. 4). We observed that the OALs prioritised NbS capable of addressing the context-specific hazard over other criteria. Yet, only OAL-Finland ranked the selection criteria using a multi-criteria analysis approach (MCA; Dean, 2020). The rest of the OALs strived to identify NbS that met as many criteria as possible. Most of the criteria were related to sustainability aspects such as the NbS being biodegradable, blending into the local landscape, improving the local ecosystem, being cost-effective, etc. However, it is worth noting that not all the OALs proposed NbS selection criteria related to using local resources, to be acceptable by multiple stakeholders, or to present potential for research and upscaling (Table 1; Fig. 4). Moreover, criteria related to environmental policy and permitting paths for NbS implementation were in general not included as criteria (Fig. 4; Supplementary Material - Table S2). It is also worth noting that the selection criteria related to NbS function and performance (i.e,, NbS capable to address the hazard, to mimic the functions of grey infrastructure, and to utilise ecosystem processes) were the only ones identified by all the OALs (Fig. 4). The latter criteria somehow relates to NbS types (e.g., Eggermont et al., 2015).

The consolidation of selection criteria enabled the OALs to shortlist a range of NbS (Table 2 and Fig. 5). NbS types ranged from soil bioengineering techniques and sustainable drainage systems (SuDS) to blue-green infrastructure and ecosystem-based adaptation approaches. The NbS shortlisting depended on three main factors: (i) hazard type, (ii) hazard scale, and (iii) OAL size. NbS related to the management of the water cycle were common to all OALs. However, OALs exposed to landslides and erosion shortlisted NbS capable to manage water budgets within the soil compartment at the local or landscape scale, while OALs exposed to floods and droughts shortlisted approaches to manage water transport and storage at the catchment scale. As a result, soil bioengineering interventions were shortlisted to address landslides and erosion, while blue-green infrastructure was shortlisted to tackle floods and droughts. The latter approaches were also shortlisted to address eutrophication in Finland, as the hazard was related to water transport between environmental compartments. Where OALs had an area greater than 1 km^2, ecosystem-based adaptation approaches tended to be shortlisted, but when this was not the case, small-scale interventions intended to address the hazard at very specific locations were shortlisted (Table 2).

Table 1. NbS selection criteria identified by the seven OALs during the co-creation process as desirable features of the envisaged NbS.

Criterion	Hazard	Shallow landslide		Deep-seated landslide	Flood	Flood & drought	Eutrophication
Criterion	OAL	UK	Italy	Austria	Ireland	Greece	Finland
Addresses hazard		X	X			X	X
Addresses hazard's drivers		X		X	X		X
Mimics grey infrastructure's functions		X	X		X		
Ecosystem processes utilisation		X	X	X	X	X	X
Biodegradable		X	X	X			
Blends into the landscape		X	X		X		
Optimises land use				X	X		
Low site disturbance						X	
Improves local ecosystems		X	X			X	X
Cost-effective		X	X	X			
Swift construction		X	X	X			
Low maintenance		X	X	X			X
Uses local resources		X					

Built with manpower (cf. construction plant)	X		X			
Community-based	X			X		
Integrates smart technology				X		
Policy compliant			X			
Adaptable to multiple land management models						X
Acceptable by multiple stakeholders	X		X	X		X
Research potential	X		X			
Upscaling potential	X	X	X	X		X

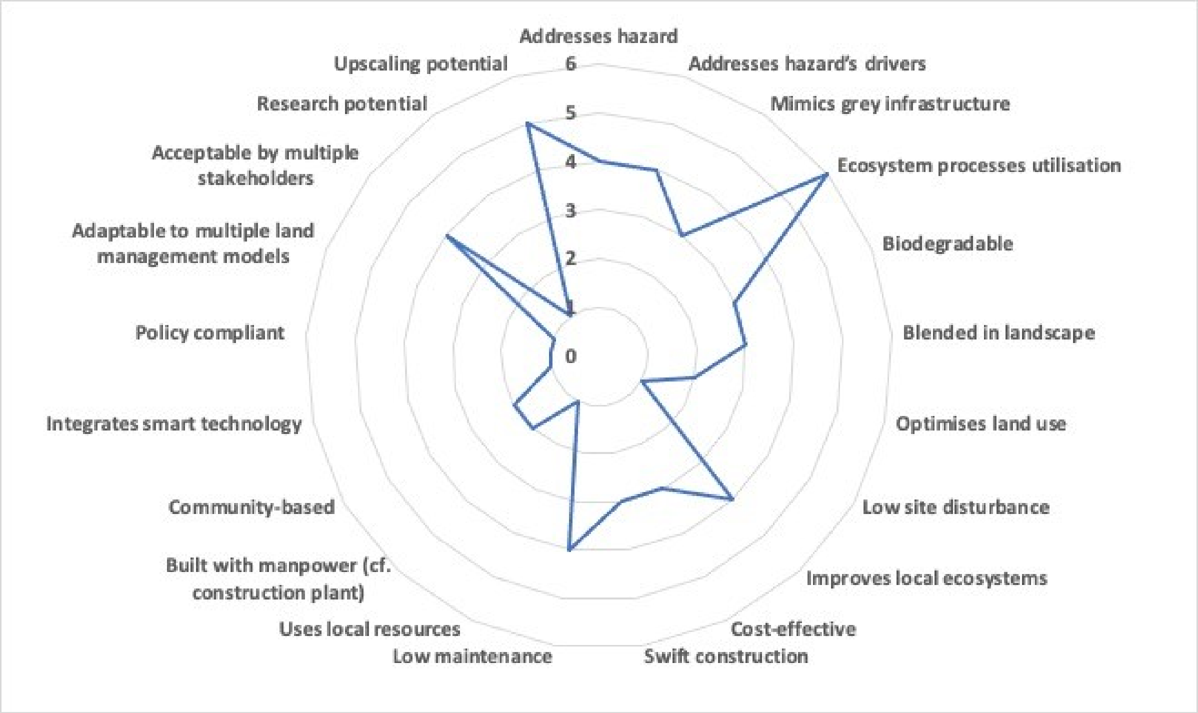


Figure 4. Spider diagram showing the NbS selection criteria resulting from the co-creation process and the number of OALs (I.e., values 0 to 6) that considered each criterion upon selecting NbS.

425 Table 2. Features and types of the NbS shortlisted by the OALs

Hazard	OAL	NbS types	NbS features	NbS shortlist
Shallow Landslide and erosion	UK	- Soil bio-engineering techniques - Green Infrastructure - SuDS	Interventions that combined inert, timber-based structures with living vegetation to promote the stability, protection, and drainage of the OAL's slopes subjected to landslides and erosion. The interventions mimicked the engineering design principles of conventional grey infrastructure whilst contributing to restore the landscape	- Live cribwall - Live grating - Live palisade - Brush layer - Live pole drain - High-density planting
	Italy	- Soil bio-engineering techniques	Deep-rooted herbaceous cover able to dissipate the stream power and resulting shear stress on the riverbank whilst providing hydro-mechanical reinforcement to the soil, contributing to regulate the embankment's water budget through drainage and plant-water uptake, and improving the soil structure through the incorporation of decaying organic matter	Herbaceous protection cover
Deep-seated landslide	Austria	- Groundwater storage - Ecosystem-based adaptation	Biodegradable streambed seal preventing stream percolation and groundwater recharge. Also, identification of forest management approaches impacting on the soil water budget and reducing infiltration of surface water and ground water recharge.	- Bentonite layering below the streambed - Forest management adaptation
Flooding	Ireland	- Blue/Green infrastructure - SuDS - Ecosystem-based adaptation	Green/blue infrastructure within the so-called SuDS and able to reduce surface runoff, enhance water storage at the catchment level, and slow down flood waves whilst being deployed within readily available urban premises such as rooftops or existing gardens.	- Smart Green roof - Rain gardens network
Flooding & drought	Greece	- Blue/Green infrastructure - Ecosystem-based adaptation	Natural water retention measure that aims to moderate the negative impact of flooding and drought on the OAL's catchment. The NBS comprises the construction of a flood storage reservoir in combination with the stabilisation of the river banks, widening of the river bed, and removal of sediment from the river bed.	Flood storage reservoirs
Eutrophication	Finland	- Ecosystem-based adaptation - Blue/Green infrastructure	Green/blue infrastructures aim to reduce surface runoff, to reduce the leaching of nutrients and suspended solids, to slow down water flow, and to promote sedimentation of the leached nutrients and suspended solids at the bottoms of the waterbodies. Changes in silviculture practices are also contemplated to reduce changes in disturbance of the forest floor and manage the leaching of nutrients and suspended solids into the water bodies	- Continuous cover forestry - Constructed wetlands - Overland flow areas - Riparian buffer zones - Sedimentation ponds - Submerged dams

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3.3. NbS selection

NbS selection in the OALs resulted from additional discussions and consultations held between stakeholders and experts in light of the shortlisted NbS and the selection criteria (Tables 1, 2, and 3; Figs. 3, 4, and 5). In most OALs, the decision process was supported by outputs from numerical models by which the performance of the NbS was tested under changing climate scenarios, land management models, or NbS designs (e.g., Gonzalez-Ollauri and Mickovski, 2017a, Gonzalez-Ollauri et al., 2021b; Spyrou et al., 2021). This was, in most cases, the only evidence academic experts could use to win support from the stakeholders in the selection process (Albert et al., 2021). In addition, the development and analysis of numerical models helped in gaining understanding of the functioning of the NbS and were used to define monitoring strategies assessing the performance of the NbS (e.g., Kumar et al., 2021; Gonzalez-Ollauri and Mickovski, 2020; Gonzalez-Ollauri et al., 2021a). However, the construction and implementation of numerical models was time-consuming (ca. 1 year per model) and their outcomes should be critically examined due to the lack of validating evidence.

The final NbS selection often depended on the feasibility of deploying an NbS for a specific context. NbS selection was also tied to the identification of suitable intervention sites in the OAL. Thus, NbS selection was pre-determined by the site features and location but, more importantly, by the ability of the OALs to fund the construction/implementation of the NbS, within a given timeframe. For example, heavy plant machinery could not access the OAL-UK, but there was local availability of timber, earth, and vegetation materials. At this OAL, the budget could not exceed £10k, so most of the work had to be carried out with manual labour. Moreover, construction works were limited to a narrow timeframe (i.e., April to June) in which the ground was workable and the vegetation materials could survive and thrive on the NbS (e.g., Schiechtl and Stern, 1996). The lack of land to implement NbS within the urban OAL of Ireland favoured solutions implementable on the available space within the city of Dublin - i.e., roofs, allotments, and back gardens. Yet, the stakeholders' perception and influence were also decisive. For example, the river Po authority in Italy preferred a very low-cost and readily implementable NbS that had no management needs as an alternative to conventional grey infrastructure, which performance has been recently questioned by this authority. Forest producers in OAL-Finland favoured NbS that were in harmony with the existing land use. Stakeholders in OAL-Ireland preferred NbS that could be easily instrumented with smart sensors and technology. The local residents in OAL-UK preferred interventions resembling conventional engineering approaches for slope stability, as these provided a feeling of safety (Anderson et al., 2022). More detail on the NbS selection process for each OAL is provided in the Supplementary Material.

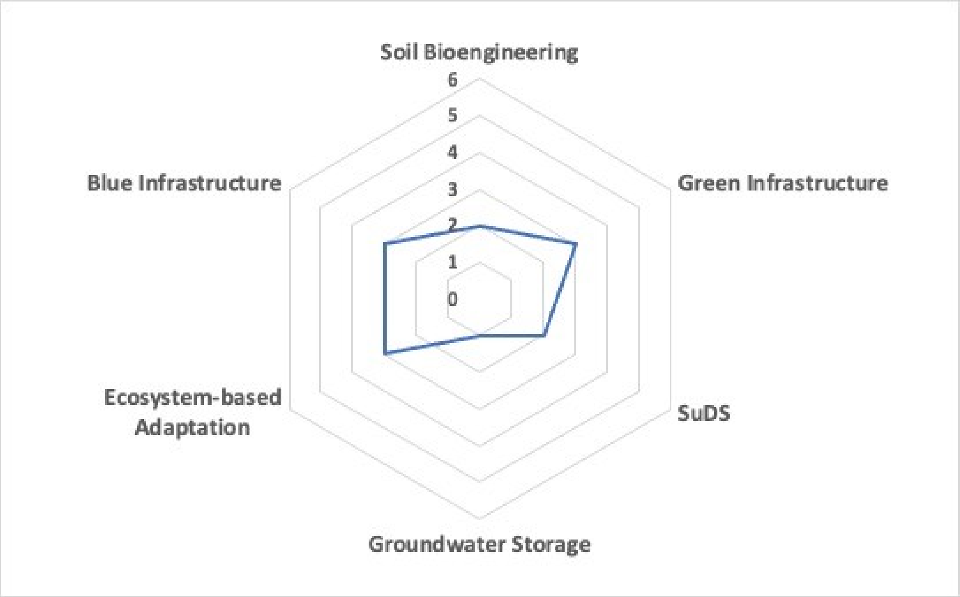

Figure 5. Spider diagram showing the NbS types shortlisted by the OALs. Values 0 to 6 indicate the number of OALs that chose a particular NBS type.

3.4. Framework for NBS selection

The proposed framework is shown in Fig. 6 and Table 3. This generic, yet integrated, framework resulted from compiling the steps and tasks undertaken in the process of selecting NbS by the OALs (Sections 3.1-3.3 and Supplementary Material). The framework is established upon three main stages: (i) problem recognition, (ii) NbS identification, and (iii) NbS selection. The framework's steps are sub-divided into more detailed tasks, which can help apply the framework more effectively (Fig. 6; Table 3).The framework is generic enough to encompass the range of climates, HMHs, and NbS covered by the six studied OALs. The framework is clear and easy to follow from the perspective of a range of stakeholders, so it can serve as a basis to inform NbS selection processes whilst facilitating the organisation of groups of diverse stakeholders for managing natural hazards.

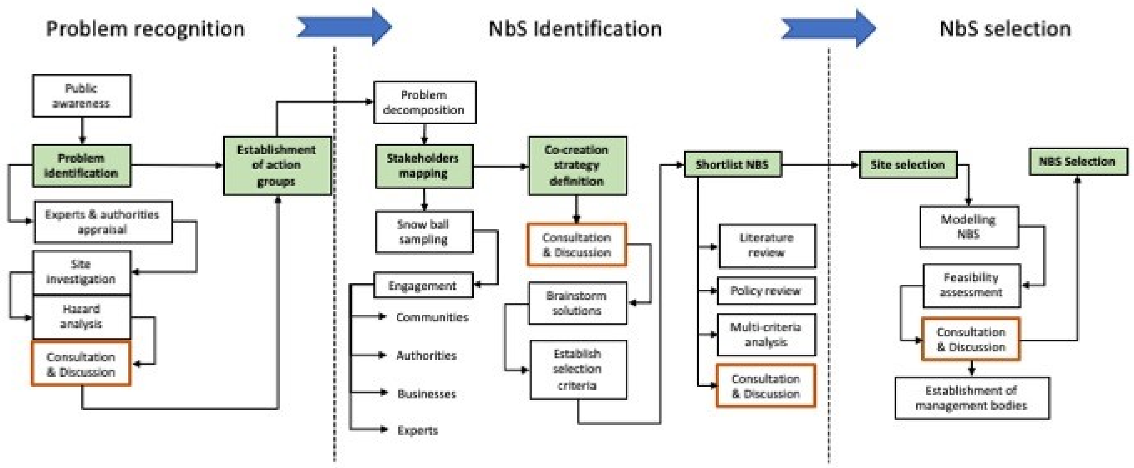

Figure 6. NbS selection framework emerging from the selection processes followed at the six OALs. The green boxes denote key steps to reach NbS selection and which grouped other sub-steps or activities for accomplishing their objectives (see Table 3).

Table 3. Stages and steps, and their corresponding aim in the process of NbS selection.

Stage	Step	Sub-step	Aim
Problem recognition	Public awareness		To increase the level of understanding about the importance and implications of an HMH
	Problem identification		To characterise the drivers, the nature, the location, the extent, and the derived consequences of a given HMH
		Experts and authorities appraisal	To assess with experts and relevant authorities the environmental, socio-economic, and political nature of an HMH and its solution prospects
		Site investigation	To characterise the context in which an HMH occurs and potential solutions will be implemented
		Hazard analysis	To understand the frequency, intensity, and extent of an HMH
		Consultation & Discussion	To seek views and advice from multiple parties on the potential to

			manage an HMH with NbS
	Establishment of action groups		To form a body/group of people to identify, implement, and manage actions against an HMH
NbS identification	Problem decomposition		To break down a problem into a set of subproblems to identify drivers and achievable solutions
	Stakeholder mapping		To draw a visual representation of the various people involved in the process of managing context-specific HMHs with NbS
		Snowball sampling	To recruit new stakeholders through those already involved in the project
		Engagement	To build trust and rapport between stakeholders
	Co-creation strategy definition		To define steps and participatory activities to share ideas, views, and knowledge between stakeholders with the aim of finding feasible NbS against an HMH
		Consultation & Discussion	To seek views and advice from multiple parties on the preferences and expectations of potential NbS
		Brainstorm solutions	To collaboratively produce spontaneous ideas and ways of addressing HMHs with NbS
		Establish selection criteria	To define desirable features of the NbS
	Shortlist NbS		To identify feasible, context-specific NbS from a pool of possible options
		Literature review	To identify existing interventions against an HMH
		Policy review	To identify the permitting paths for the implementation of NbS in a given context
		Multi-criteria analysis	To identify and compare multiple NbS options in light of their features

		Consultation & Discussion	To seek views and advice from multiple parties on the perception and preference of multiple NbS with the aim of creating a shortlist
NBS Selection	Site selection		To choose a hazard-prone zone for implementing an NbS
		Modelling NBS	To foresee the performance of an NbS against an HMH for informing design and construction
		Feasibility assessment	To assess the ecological, engineering, economical, and social practicality of a given NbS for a given context
		Consultation & Discussion	To seek views and advice from multiple parties on the feasibility of a shortlist of NbS
		Establishment of management bodies	To form a body for managing the implementation and subsequent maintenance of NbS
	NbS selection		To select a specific NbS against an HMH as the most suitable for a given context

The proposed framework reflects the experiences of the stakeholders involved and, as such, it is inclusive and integrated. The end-users are included firmly as creative partners in the centre and throughout the process (e.g., IUCN, 2020b; Ruangpan et al., 2021). Hence, the proposed framework lends itself to co-creation, co-design, and co-deployment. It is worth noting that, in the case of the OALs, the end-users were the communities within and adjacent to the OALs. The intrinsic value of the proposed framework lies in the use of the ideas by the end-users which are richer and unstructured, yet they are captured in a structured manner in the framework. The concept of co-creation taken in this study involved as many and varied stakeholders as possible throughout the identification and selection processes. With the latter, the OALs strived to get a common consensus from the different ideas, designs, and justifications of the selected NbS, trying to fit all or most of the selection criteria (Table 1). However, this approach could reduce the involvement of, for example, the commercial designers and/or technology providers if an appropriate financial incentive were not to be presented. In this respect, future work on the development and enhancement of the proposed framework should see an integration of financial viability criteria, which can contribute to a more robust feasibility assessment (e.g., Croeser et al., 2021). The perceived relatively low cost of NbS (Maxwald et al., 2020) should preclude focussing solely on the financial aspect of the solution, as is often the case in infrastructure projects (e.g., Mickovski, 2014), and put environmental, engineering, and societal concerns at the forefront of NbS selection.

The proposed framework also has inevitable limitations. These result from relying on stakeholder and expert judgement of the steps to be followed in the selection processes (Table 3). The NbS identification and selection stages can profit from evidence-based approaches focusing on direct observations. Though still lacking, factual clarity on NbS will help bridge the perceived gap between the scientific and engineering discourse and the NbS debate in practice, where real-world problems need to be addressed for the benefit of the end-users regardless of the applied concepts (e.g., Hanson et al. 2020, Albert et al. 2019). To this end, the users of the proposed framework can refer to various syntheses of NbS selection criteria (e.g., Davis et al., 2018), or lessons learned from historic NbS projects (e.g., Castellar et al., 2021). However, the basis of our framework maintains the multi-dimensional evaluation of NbS. It also ensures transdisciplinary connections with the inclusion of a wide range of stakeholders, which is often seen as a difficulty when similar approaches are considered (e.g., Albert et al. 2019, 2021). Additionally, the proposed framework is overall well-aligned with existing NbS selection processes and frameworks (e.g., Albert et al., 2021; Ruangpan et al., 2021; IUCN, 2020b; Croeser et al., 2021; Gonzalez-Ollaui et al., 2021a). For example, our framework agrees with the one proposed by Albert et al. (2021) in that the problem recognition stage should be addressed first and holistically. It also follows IUCN's guidance regarding Criterion 5 (IUCN 2020b), which suggests that the stakeholder mapping and co-creation processes should be carried out rigorously. Our framework also agrees with the findings highlighted by Ruangpan et al. (2021), which stress the need to establish site constraints, the need to understand stakeholders' perception, and the need to place the spotlight on the identified problem.

Future enhancement of the proposed framework should see its application accompanied by an assessment of the sustainability performance at each stage of the NbS selection process. This assessment can be carried out using existing approaches (e.g., Mickovski and Thomson, 2017; Gonzalez-Ollauri et al., 2021; Mickovski et al., 2022), which can, then, be used as a planning tool for the next steps in the NbS construction process. As mentioned earlier, the performance assessment will have to include the environmental, societal, financial, and engineering aspects of each NbS to have a common basis for comparison and selection. High scores on the sustainability of one of these aspects should not mask the overall sustainability performance of NbS over the whole lifecycle. Hence, it is essential that the proposed framework is extended to capture the experiences of the OALs with the latter stages of NbS application such as co-deployment, co-monitoring, etc. Such development would be harmonious with the spirit in which the proposed framework has been envisaged, with the end-users firmly in the centre of the process. This approach supports capacity resilience and building in the OALs' communities, especially in the areas of sustainability that were identified as lacking during the NbS selection process (e.g., criteria related to selection of local labour and materials, stakeholder engagement, and/or potential for upscaling). Although training and professional development would be needed for all of the stakeholders engaged in an NbS project, it will not be difficult to provide it in the form of workshops and panel discussions once there is a coherent stakeholder base that is ready to apply the principles of co-creation and co-design. This approach may be more appropriate at a strategic level with long timeframes, but it can be made more useful when NbS practitioners are learning new techniques at the scale of individual NbS, projects or OALs as opportunities emerge. These capacity-building events would be a logical continuation of the discussions held at the problem recognition, NbS identification, and selection stages, they can be organised in-person and/or online, and they can be, if needed, organised to include experiences and testimonials of similar projects nationally and internationally to help overcome the issues identified by existing approaches (e.g., Croeser et al, 2021)

The proposed framework can be easily upscaled from OAL to landscape scale because, at its base, it supports a trans-boundary context which is needed for implementation of EU directives/strategies, such as the EU Strategy on Green Infrastructure (EC, 2022) or EU NbS research policy (EC, 2018). Although the NbS applied at the OALs are at a relatively low exploitation or readiness level, the application of the proposed framework can help open up a discussion forum at regional and trans-national level. At this forum, issues such as the upscaling of the NbS implemented by the OALs can be discussed, together with the integration of larger stakeholder groups which will, in turn, lead to exploring possibilities for regional and trans-boundary infrastructure investment. This approach can encourage the NbS co-design process to consider new technologies, economic, and social priorities with meaningful contributions from not only the communities exposed to HMHs but also from academia, business, engineering membership bodies, and intergovernmental organisations. This approach envisages that issues identified in the OALs, such as the development of engineering design and predictive models for NbS performance, will be overcome by providing opportunity for validation of these models based on their (un)successful application through co-deployment processes.

4. CONCLUSION

We aimed at creating a new framework for NbS selection stemming from real practice. To this end, we investigated the process of selecting NbS followed at six open-air labs (OALs) distributed across Europe and subjected to different hydro-meteorological hazards (HMHs), such as landslides, floods, droughts, and eutrophication. We also synthesised the multiple NbS selection processes and merged them into one integrated framework.

We found that the process of selecting NbS was overall complex and context-specific. The selection process comprised 26 steps distributed across three stages: (i) problem recognition, (ii) NbS identification, and (iii) NbS selection. We also confirmed with other studies that thorough problem and site characterisation, and the close involvement of multiple-level stakeholders through an open co-creation process, are both essential to identify criteria for selecting NbS effectively. Herein, we identified over 20 selection criteria which, in most cases, were shared across OALs. Most of the criteria were related to sustainability aspects. Yet the only common criterion to all the OALs was that the NbS should utilise ecosystem processes. Moreover, not all the OALs considered criteria related to the acceptability of the NbS by stakeholders, related to the use of local resources, or to the required permitting paths for building the NbS, suggesting that the list of criteria provided herein should be viewed with criticism.

We observed that the NbS were chiefly chosen according to three main factors: (i) hazard type, (ii) hazard scale, and (iii) OAL size. The types of NbS selected ranged from soil bioengineering techniques and sustainable drainage systems (SuDS), to blue-green infrastructure and ecosystem-based management and adaptation approaches. We noticed that the largest OALs, with areas greater than 1 km^2, tended to shortlist ecosystem-based management approaches, while the smallest OALs preferred small-scale NbS targeting the hazard at specific locations. It is worth noting that all the NbS shortlisted were related to the regulation of the water cycle.

However, OALs exposed to landslides and erosion selected NbS for managing water budgets within the soil compartment at the local or landscape scale, while OALs exposed to floods, droughts, and eutrophication chose approaches for managing water transport and storage at the catchment scale.

The proposed framework successfully portrays a synthesis of the stages and steps followed in the NbS selection processes by the six investigated OALs. The framework, which reflects the experiences of the stakeholders involved, is inclusive and integrated. We also think that it is clear and easy to follow, so it can serve as a basis to inform NbS selection processes whilst facilitating the organisation of diverse stakeholders striving to address natural hazards. We animate future development of the proposed framework by integrating steps related to assessing the financial viability of the NbS at the identification stage to contribute to a more robust feasibility assessment at the selection stage. We also encourage studies looking into the implementation of the proposed framework through quantitative approaches using multi-criteria analyses. To this end, we also recommend an assessment of the sustainability performance at each stage of the NbS selection process.

Credit authorship contribution statement

Conceptualisation: AGO
Data collection: AGO, ML, JP, DP, FP, SS, ET, LU, TZ
Investigation: AGO
Data curation: AGO
Writing – original draft preparation: AGO, SBM, CCA, SD, JO
Writing – review and editing: AGO, SBM, CCA, SD, PK, ML, JO, JP, DP, FP, SS, ET, LU, TZ
Supervision: SBM, RE
Project administration: AGO, RE
Funding acquisition: RE, PK
All authors have read and agreed to the submitted version of the manuscript.

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