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Review

Towards an operationalisation of nature-based solutions for natural hazards

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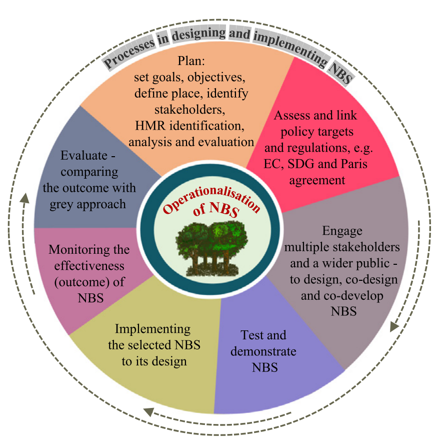
HIGHLIGHTS

- HMHs negatively affect human life and economy in Europe and globally.
- There is an emerging need to improve coherence between DRR and NBS in Europe.
- Integrating and cataloguing of NBS into policy databases is still at an early stage.
- Links between science and stakeholders are hampered by lack of effective communication.
- Practical implementation of NBS needs a holistic approach, complementary tools and instruments.

GRAPHICAL ABSTRACT



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ABSTRACT

Nature-based solutions (NBS) are being promoted as adaptive measures against predicted increasing hydrometeorological hazards (HMHs), such as heatwaves and floods which have already caused significant loss of life and economic damage across the globe. However, the underpinning factors such as policy framework, end-users' interests and participation for NBS design and operationalisation are yet to be established. We discuss the operationalisation and implementation processes of NBS by means of a novel concept of Open-Air Laboratories (OAL) for its wider acceptance. The design and implementation of environmentally, economically, technically and socio-culturally sustainable NBS require inter- and transdisciplinary approaches which could be achieved by fostering co-creation processes by engaging stakeholders across various sectors and levels, inspiring more effective use of skills, diverse knowledge, manpower and resources, and connecting and harmonising the adaptation aims. The OAL serves as a benchmark for NBS upscaling, replication and exploitation in policy-making process through monitoring by field measurement, evaluation by key performance indicators and building solid evidence on their short- and long-term multiple benefits in different climatic, environmental and socio-economic conditions, thereby alleviating the challenges of political resistance, financial barriers and lack of knowledge. We conclude that holistic management of HMHs by effective use of NBS can be achieved with standard compliant data for replicating and monitoring NBS in OALs, knowledge about policy silos and interaction between research communities and end-users. Further research is needed for multi-risk analysis of HMHs and inclusion of NBS into policy frameworks, adaptable at local, regional and national scales leading to modification in the prevalent guidelines related to HMHs. The findings of this work can be used for developing synergies between current policy frameworks, scientific research and practical implementation of NBS in Europe and beyond for its wider acceptance.

Contents

1. Introduction

Hydro-meteorological hazards (HMHs) are a subcategory of natural hazards originating from atmospheric, hydrological or oceanographic processes, which cause severe socio-economic disruptions and damages, such as loss of lives, services, livelihoods, properties and environment (UNISDR, 2015). They were responsible for more than 80% (502.56 billion USD) of the total economic damage due to natural hazards (618.5 billion USD) and caused around 90,325 fatalities in Europe during the period from 1980 to 2017 (EEA, 2019). Risks associated with HMHs are recognised through their frequency, severity and the extent of the damages. Changes have been observed in these HMH risks and they are projected to increase under climate change (Quevauviller and Gemmer, 2015). For example, heavy precipitation (Berg et al., 2013; Gallant et al., 2013; Trenberth et al., 2014; Scherrer et al., 2015; Fischer et al., 2014), floods (Rojas et al., 2012; Alfieri et al., 2015, droughts (Spinoni et al., 2015), heatwaves (Donat et al., 2013; Russo et al., 2015; Zampieri et al., 2016; Guerreiro et al., 2018), landslides (Stoffel et al., 2014), forest fires (Lindner et al., 2010; Carvalho et al., 2011; Dury et al., 2011; Vilén and Fernandes, 2011) and storm surges (Bondesan et al., 1995; Wakelin and Proctor, 2002; Lionello et al., 2006; Vousdoukas et al., 2016) are among the most frequent and anticipated extreme HMHs projected to increase in frequency and/or magnitude in the future.

The management of these HMHs has relied on non-structural (e.g. forecasting, early warning, land use planning, emergency services and evacuation) and structural/engineered (e.g. dykes, seawalls and levees) measures, or a combination of both, depending on the location (Jones et al., 2012). The non-structural measures allow for *crisis* and *risk* management by providing resource supply during HMH occurrence, while the structural measures aim at resisting HMH intensity and frequency. However, such traditional engineered or grey approaches usually do not solve the root cause of the hydrometeorological risks (HMRs) and may make people and ecosystems even more vulnerable over the long-run of time (Depietri and McPhearson, 2017).

The growing recognition that traditional measures will not be able to cope with the increasing and intensification of HMR with climate change, has urged the involvement of respective field-experts and policymakers for devising and implementing more adaptive, cost-efficient, resilient, sustainable and environment-friendly HMR management measures. For instance, climate change adaptation (CCA) and disaster risk reduction (DRR) measures are supporting the advancement of the policy framework for sustainable and cost-effective options to address the impacts of climate change on water availability, people and their properties (Kabisch et al., 2016). These measures are closely connected with a range of European policies, legislations and global agendas, such as the Sendai Framework for Disaster Risk Reduction (2015–2030) (UNISDR, 2015), the Sustainable Development Goals (SDGs) (UNDP, 2015) and the Paris Climate Agreement (UN, 2015). Nature-based solutions (NBS) are one of such measures that were encouraged by these global summits as an effective alternative for addressing societal, financial and environmental problems caused by climate change.

NBS is a notion that relies upon and combines various resource-efficient and holistic ecosystem approaches for their multiple evaluated societal and financial benefits (Eggermont et al., 2015) by bringing together science, funds, policy, legislation and innovation (European Commission, 2015). NBS is designed and operated based on eight basic principles suggested by IUCN (2016), according to which NBS is a holistic approach integrating both the engineering and ecosystem component in its implementation. Currently, NBS is encouraged in both research and practice, and being referred to in policy/decision-making processes with an aim to further developing and synergising the knowledge base among the science, policy and practice (Droste et al., 2017). The European Commission (EC) is playing a major role in this respect by making NBS as part of Horizon 2020 (H2020) framework programme for research and innovation which allocated approximately €185 million to the topic between 2014 and 2020. Through H2020 and other EU funding mechanisms, the EC has funded numerous NBS projects aiming to the broad operationalization of ecosystem-based approaches to reduce HMRs across Europe and the world (European Commission, 2016). The advent of European and international policies for HMRs management using NBS is further enhancing the holistic approach of NBS worldwide (Section 6). Table 1 shows a comprehensive list of past and ongoing projects addressing HMRs through NBS. The foci of these projects are complementary, mostly built on the principles of sustainable growth, and comprise aspirational goals to improve both human welfare and ecosystem performance against HMRs. Many of them deal with the urban environment but all of them contribute to the common effort of promoting, upscaling and replicating NBS in Europe and worldwide.

However, when compared to traditional approaches, NBS is rarely considered as a first choice by relevant stakeholders to reduce HMRs. There are several reasons for this. Firstly, the transition from the concept of NBS to its actual operationalisation is still hindered by the significant gap in NBS data and science-based information usable for policy and decision-makers. Secondly, despite the comprehensive work on well-functioning ecosystems and their services in recent years, we still lack practical understanding about the variety of stakeholders, their interests, perception and preferences over numerous types of NBS against HMRs, especially in rural and natural territories. For instance, a wealth of information about NBS case studies is already available (Debele et al., 2019), still there exists a necessity for integrating NBS into guidelines and their dissemination through policy platforms and publications. Thirdly, the fragmented NBS policies, knowledge gaps regarding NBS designing, and missed linkages in the existing literature make difficult to translate the concept of NBS into practice. For example, numerous review papers have addressed the role of NBS in managing climate extremes and recommended ways forward to implement NBS for CCA (Table 2), but information on their operationalisation mechanism is missing. Furthermore, a majority of these articles focused either on NBS for HMR reduction with less/no emphasis on policy regulation (Bennett et al., 2015; Faivre et al., 2018; Debele et al., 2019; Sahani et al., 2019) or on the significance of multidisciplinary and inclusive approach for NBS implementation, with no or limited focus on their relevance to specific HMHs (Nesshöver et al., 2017, Raymond et al., 2017, Kabisch et al., 2016). For instance, some authors have discussed European policies and adaptation actions for climate change and water-related risks but lack referring to specific HMRs and their respective NBS (Rauken et al., 2015; Pietrapertosa et al., 2018; Quevauviller, 2011). Overall, the two major knowledge gaps that emerged from the review of relevant literature in Table 2 are the lack of policy framework relevant for the application of specific NBS to specific HMHs, and limited knowledge on end-user interests and their participation in the NBS operationalisation process.

Thus, the goal of this review paper is to analyse the published literature on NBS as a long-term measure for HMH mitigation and reduction, incorporating relevant indicators, policies and stakeholders for its effective implementation and operationalisation. In particular, we briefly highlight the trends, damages and indicators for five selected HMHs in Europe and introduce the concept of open-air laboratories (OALs), its role, relevant policy frameworks and practical aspects in the operationalisation of NBS.

2. Methods, scope and outline

We carried out a systematic literature review (SLR) by pursuing the concept of 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)' approach for locating the relevant literature (Moher et al., 2009; Shamseer et al., 2015). Supplementary Information (S1) Fig. S1 shows the procedure followed, the number of papers included and reasons for exclusion of other papers. A string of keywords (Table S1) was applied in three scientific databases: Web of Science, Scopus and ScienceDirect to perform searches, and a record of scientific papers and reviews deemed for full-text review was compiled. These databases are comprehensive and cover a broad range of disciplines. The reviewed literature was limited to articles written in English and published between 1979 and 2019. Some applicable literature might have been eliminated from our review due to: (1) search string adopted and (2) the language of publication. The search in these scientific databases resulted in 4500 articles (SI Fig. S1). To include peer-reviewed papers from a journal that might not be indexed in these three scientific databases, we repeated the search procedure in 'Google Scholar', resulting in a total of 250 articles and 53 credible reports. In the screening procedure, we followed the basic steps given in SI Fig. S1 against lists of selection criteria.

Out of 4072 articles (after removing duplicates), 3000 publications were eliminated from full-text review based on their titles and abstracts. We also carried out a further screening to include only the most suitable scientific papers and eliminated 845 papers from 1072 papers based on types of hazards, the policy framework for NBS to reduce HMR, language and location of study. The procedure led to a total of 227 articles to be analysed and discussed in this review. The distribution per topic area of the selected literature showed that 31% of the papers dealt with HMH/HMR, 24% addressed policy, 10% covered stakeholder

Table 1
Summaries of past and ongoing projects working on NBS (2007–2022).

Projects related to NBS	Targets and summary	Reference
TURaS	Offers examples of approaches for enhancing urban sustainability, e.g. green walls that can be adopted in any location and at an affordable cost.	Turas (2019)
GREEN SURGE	Prepared the strategies to design urban green approaches: integrating green and grey approaches, connecting green areas, utilising the multipurpose character of the green approach and involving citizens in urban planning.	Greensurge (2019)
OpenNESS	Shows NBS (green infrastructure) integrated urban planning in and around Vitoria-Gasteiz (Spain) for improved and energy-efficient water-flow regulation, enhancement in biodiversity, health and habitat (air, noise and heat).	Openness (2019)
OPERAs	Combined NBS with traditional ones by constructing and maintaining semi-fixed dunes on Barcelona's (Spain) urban coastline to optimise ecosystem benefits and augment coastal defence against sea-level rise.	Operas (2019)
CONNECTING NATURE	Brings in actions to feed the initiation and expansion of economic and social enterprises in production and large-scale implementation of NBS in urban settings to measure the impact of these initiatives on climate change adaptation, health and well-being, social cohesion and sustainable economic development.	Connecting Nature (2019)
GrowGreen	Aims to invest in NBS (high-quality green spaces and waterways) while long term city planning to develop climate and water resilience, strong and habitable cities, capable of dealing major urban challenges, such as flooding, heat stress, drought, poor air quality, unemployment and biodiversity-loss.	Growgreen (2019)
UNaLab	Aims to develop a European Reference Framework on benefits, cost-effectiveness, economic viability and replicability of NBS by promoting smart, inclusive, resilient and sustainable urban communities through co-creation (with and for local stakeholders and citizens) of Urban Living Lab (ULL), demonstrations, experiments and evaluation of NBS for climate and water challenges.	Unalab (2019)
URBAN GreenUp	Aims to develop, apply and validate a methodology for Renaturing Urban Plans to mitigate the effects of climate change, improve air quality, water management and increase the sustainability of cities through innovative NBS.	UrbanGreenUP (2019)
NATURVATION	Assesses NBS achievements in cities, examines their innovation process and works with communities and stakeholders to develop the knowledge and tools required for the recognition of NBS potential for meeting urban sustainability goals.	Naturvation (2019)
Nature4Cities	Aims for a positive balance between economic, environmental and societal benefits and costs by creating a reference platform for NBS, offering technical solutions, methods and tools for urban planning. This balance entails collaborative models from citizens, researchers, policymakers and industry leaders through co-creation processes.	Nature4cities (2019)
NAIAD	Planned to provide a strong framework for evaluating the insurance value of ecosystem services by co-developing, co-testing and involving main insurers and local authorities, then validation and application of business model throughout Europe.	Naiad (2019)
OPERANDUM	Developing a set of co-designed, co-developed, deployed, tested and demonstrated innovative NBS for the management of the impact of HMRs, especially focused in European rural and natural territories, facilitating the adoption of new policies for the reduction of HMRs via NBS and their promotion.	OPERANDUM (2019)

engagement, 19% covered NBS while 16% covered other concepts (i.e. climate change, cost-benefit analysis etc). SI Fig. S2 lists the number of full-text publications included in this review. All these publications have been organised by year and 2019 was the year with the maximum number of publications.

The scope of this paper is limited to the following HMHs – floods, droughts, landslides, coastal erosion and storm surge, and nutrients and sediment loading. These hazards were selected because: (1) they have increased in their frequency and intensity in recent years, causing significant loss of life and economy in Europe (Fig. 1); (2) they tend to become more severe under climate change scenarios (Forzieri et al., 2016), (3) a significant percentage of areas, suitable for NBS application and with valuable ecological and cultural heritage, are vulnerable to these hazards in Europe (Trillo and Petti, 2016).

The article is structured as follows. We start with a brief overview of HMH trends and related damages in Europe in Section 3 and then discuss the set of indicators needed for monitoring each specific type of HMHs and its management through NBS (Section 4). Potential role and effectiveness of NBS for HMHs reduction are presented using OALs as a novel concept in Section 5. A review of European and international policies for HMHs and implication for NBS is presented in Section 6. Section 7 discusses the practicality of NBS including their market opportunities, cost-effectiveness and designing strategies with stakeholders for HMRs reduction. Summary and conclusions are drawn in Section 8, highlighting the research gaps and potential way forward for the operationalisation of NBS for HMHs.

3. HMH trends and damages in Europe

The increase in frequency and intensity of HMHs across Europe has been widely documented and mostly linked to climate change (IPCC, 2018; Kreibich et al., 2014). For example, trends in current and future flood risk across Europe have been anticipated to rise based on a 100-year return period as a result of a pronounced increase in heavy precipitation (Rojas et al., 2012; Forzieri et al., 2016). Blöschl et al. (2017) analysed changes in flood timing using a seasonal approach and found that north-eastern Europe is facing earlier spring snowmelt floods due to short winter and early onset of spring. Flooding due to heavy precipitation (Bouwer et al., 2010; Jonkman and Vrijling, 2008) and high intensity and short duration convective storms (Ban et al., 2015) are also expected to become more intense in the upcoming years. Likewise, a 100-year return period for future heatwave risk has shown a progressive and strong increase in frequency all over Europe (Forzieri et al., 2016; Guerreiro et al., 2018). Drought has also become a recurring feature of the European climate in recent decades (EEA, 2019). Many studies (e.g. Sepulcre-Canto et al., 2012; Spinoni et al., 2019) have predicted an increased drought risk in Mediterranean and Carpathian region as a result of climate change. Future projections in 100-year return period of drought risk indicate that droughts may become more extreme and persistent in southern and western Europe, while northern, eastern and central Europe may experience a strong reduction in drought frequency (Spinoni et al., 2015; Forzieri et al., 2016). Storm surge is another natural hazard, which has severely affected many parts of the world (IPCC, 2018) and caused increased rates of coastal erosion, particularly in areas where cliffs or shorelines are composed of loose soil and/or soft rocks. Conversely, the risk of storm surge has been projected to decrease progressively in terms of frequency and intensity over some coastal regions of Mediterranean countries (Marcos et al., 2011).

Table 2
Summary of past review articles discussing the use of NBS for HMRs reduction.

Article focus	Key finding	Reference
The use of NBS for HMH management, their classification, cost benefits and databases	The impact of HMHs such as floods, landslides, droughts, heatwaves and storm surges were effectively reduced with the use of NBS, particularly hybrid approach for flood and green approach for heatwaves are the most effective solution. But, the effectiveness of NBS depends on its architecture, typology, green species and environmental conditions.	Debele et al. (2019)
Methodologies to evaluate HMH risks and management by NBS, focused on floods, droughts and heatwaves	Different methodologies incorporating exposure, vulnerability and adaptation interaction of the elements at risk were reviewed for HMR assessment, such as fuzzy logic and statistical methodology. NBS for HMR management were promoted and pushed for more research to enhance their wider significance for building adaptations and resilience.	Sahani et al. (2019)
The use of the ecosystem approach for the reduction of disaster risks, provide sustainable solutions and enhance the implementation of 'Sendai Framework' in Europe – from policy to practice.	The application of the ecosystem approach for disaster risk management can enhance the resilience of society and environment in the city, landscape and wilderness regions and per se, helping to apply the new 'Sendai Framework for Disaster Risk Reduction 2015–2030', while also helping to attain other policy goals such as from 'biodiversity conservation to climate change adaptation'.	Faivre et al. (2018)
Adaptation measures across 11 south-east European countries with a focus on the policies and actions supported by Europe and employed at a national level.	A close collaboration between all participants engaged in the adaptation procedures is needed to create a wider agreement on adaptation approaches. Interdisciplinary measures should be fostered to evade downside effects and to utilise synergies and prospects.	Pietrapertosa et al. (2018)
The implication of NBS among science, policy and practice focused on the European context	To realise the full potential of NBS, their development and co-development must comprise the experience, interest and perception of all appropriate end-users so that 'solutions' help to accomplish all components of sustainability.	Nesshöver et al. (2017)
A framework for the assessment of NBS co-benefits, implementation of NBS, engaging stakeholders from science, policy and practice.	They transformed the theoretical framework to practical relevance by giving a seven-phase procedure which could foster NBS operationalization. Challenges tackled by NBS are multifaceted and complex, thus the choice and evaluation of NBS associated measures need the involvement of a broad range of stockholders, interdisciplinary groups and policy/decision-makers.	Raymond et al. (2017)
The potential of NBS for CCA and in urban contexts, identify indicators for evaluating the effectiveness of NBS and associated gaps.	Developed indicators for assessing the effectiveness of NBS and associated gaps via an inter and multi-disciplinary workshop with stakeholders from research, municipalities, policy and society. They concluded three main points for future research and policy plans when dealing with NBS (Kabisch et al., 2016).	Kabisch et al. (2016)
Integrating biodiversity, ecosystem services and human welfare: difficulties for designing research for feasibility.	Ecosystems and their benefits are produced by 'social-ecological systems', in which location, biodiversity, and socio-technical alteration play a crucial role. To link ecosystem services with science and practice: (1) more collaboration required and (2) co-production of knowledge via research that involves decision-makers, use of NBS to ensure that policies have a significant impact and work across many scales.	Bennett et al. (2015)
The mainstreaming of climate change adaptation in five municipalities across Norway.	Upon the application of the concepts of mainstreaming and policy integration, the policy advancement is slower, but maybe more solid in the local authorities that have selected a 'horizontal, cross-cutting approach to mainstreaming' than in the local authorities that have chosen a 'vertical sector approach to mainstreaming'.	Rauken et al. (2015)
Decreasing risks posed by water-related hazards in Europe – EU policy and research considerations.	Effective action for climate change adaptation will be closely associated with our ability to incorporate scientific knowledge in Europe 'water and climate policy cycle', which needs the advancement of research–policy linking systems.	Quevauviller (2011)
The applicability of ecosystem services in policy and decision-making processes.	There are many challenges to make the ecosystem services framework acceptable, reproducible, expandable, and sustainable. These include: (1) scientific difficulties for ecologists and social scientists, in understanding how human measures influence ecosystems and (2) challenges in convincing politicians to integrate ecosystem services into decision making. To overcome this, we ought to plan effective and involve organizations to follow-up, monitor and give incentives that consider the societal values of ecosystem services	Daily et al. (2009)

Nevertheless, the risk continues to increase rapidly in many vulnerable European coastal locations, particularly in northern and western Europe, causing substantial environmental destruction, financial losses and other societal challenges (Vousdoukas et al., 2016; IPCC, 2018). In the northern Adriatic Sea, for example, the risk of coastal flooding and erosion has become significantly high because of natural subduction of the Adriatic plaque under the Apennines at a rate of about 1 mm per year (Lionello et al., 2006). In this and other geographic areas, the situation is expected to further exacerbate as IPCC (2018) has predicted the mean sea level rise between 0.45 and 0.98 m by the end of the 21st century under Representative Concentration Pathway (RCP8.5). Based on a literature review, Gariano and Guzzetti (2016) composed a map

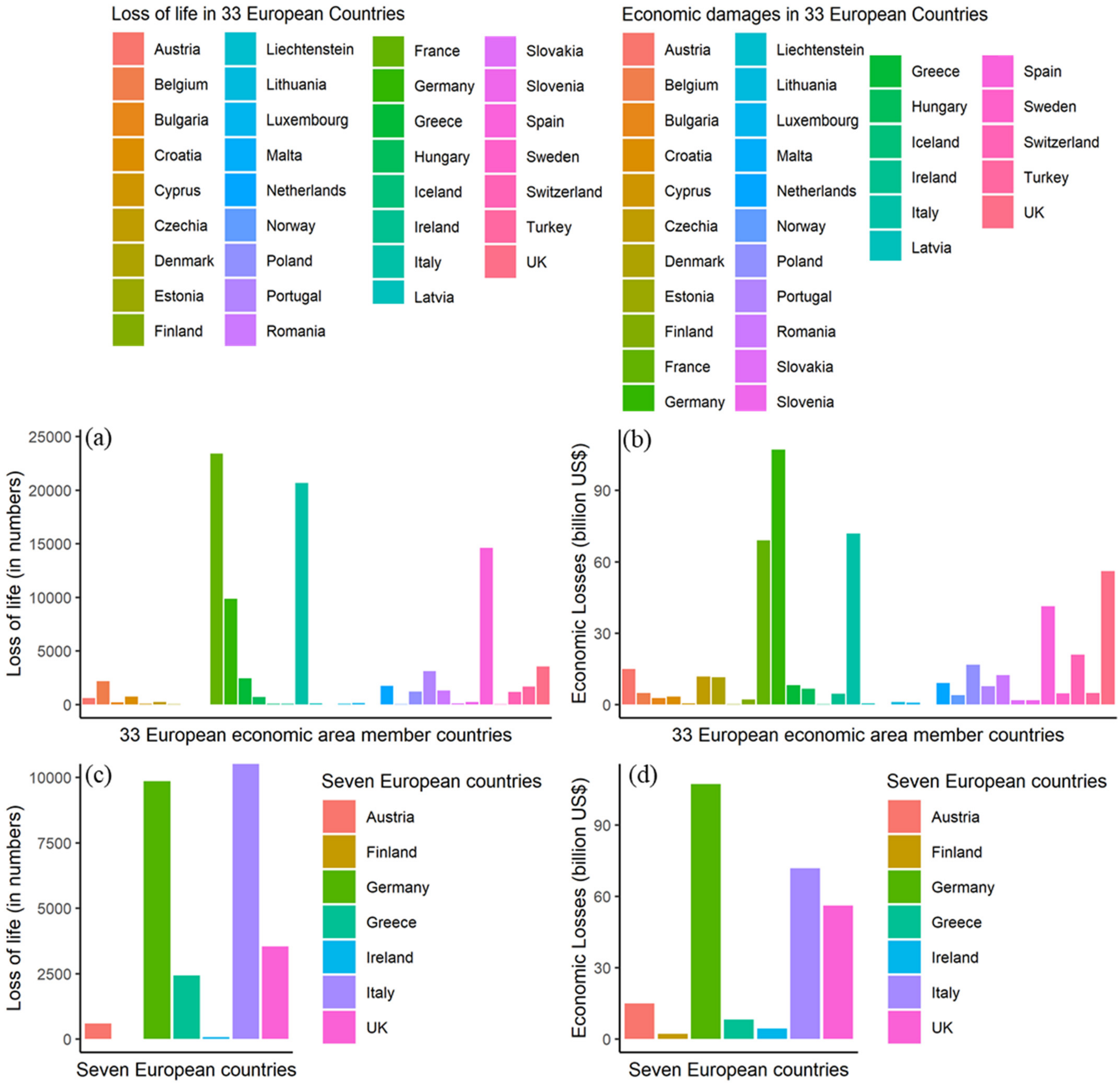


Fig. 1. (a) Loss of life, (b) economic damages in 33 European countries, (c) loss of life, (d) economic damages in seven OPERANDUM focused European countries due to the impacts of HMHs during the period 1980–2017 (Munich Re, 2019).

showing predicted global variations in landslide occurrences and types as a response to climatic conditions. They predicted a higher frequency of rockfalls/avalanches, debris flows and shallow landslides than deep-seated landslides across Europe.

Climate change-induced threats are anticipated to become more pronounced in regions vulnerable to multiple hazards, such as floods, droughts and heatwaves. For example, Forzieri et al. (2016) studied the overall exposure of European cities to multiple (independent) hazards using a comprehensive multi-hazard assessment throughout the 21st century and analysed the trends in the frequency of six HMHs (floods, droughts, wildfires, windstorms, and heat and cold waves) using climate projections. The overall exposure of Europe to this multi-hazard scenario showed a more accelerated upward trend as compared to that for the single-hazard scenarios. The connections between global warming and weather extremes are inherently complex. Their feedback mechanisms and cascading impacts are non-linear and difficult to quantify in current climate models, posing a challenge to the scientific community involved in disaster mitigation and risk management (Ferrarin et al., 2013). Nevertheless, the linkages between weather extremes and their impacts on the economy, ecosystems and people's safety are evident and further testified by the alarmingly increasing number of HMHs-related disasters reported by the EEA and other sources in 2019 (EEA, 2019; EM-DAT, 2019).

We selected EM-DAT and Munich Re-NatCatSERVICE databases among others (see Debele et al., 2019 for the complete list) based on accessibility, usability and types of hazards included to perform a statistical analysis and capture the spatial distribution of HMH fatalities and economic damages across Europe for the periods of 1900–2019 (EM-DAT, 2019) and 1980–2017 (Munich Re, 2019). In the Munich Re (2019) database, for the last 38 years (1980–2017) the total reported loss of life resulting from HMHs in Europe was approximately 90,325 with France having the greatest number of fatalities (Fig. 1a). The analysis of EM-DAT (2019) database for the last 120 years (1900–2019) shows economic losses of approximately 502.6 billion USD with the highest figure in Germany (Fig. 1b). The damages caused by specific HMHs, such as droughts, landslides, heatwaves and floods in several European countries over the last 120 years (1900–2019) are presented in Fig. 2 (EM-DAT, 2019). Flooding caused the largest economic damages (76.2%), followed by droughts (13.9%), heatwaves (8.4%) and landslides (1.5%). 54.8% (47.1% for flood and 7.7% for other hazards) of these total economic damages occurred in the seven countries where the OAL concept is being initialised for NBS operationalisation (OPERANDUM, 2019) and 45.2% in the rest of Europe (SI Table S2). In Germany, floods caused great economic losses of about 12.9 billion USD in 2002 and 7.8 billion USD in 2013 (Thieken et al., 2005; Hattermann et al., 2014; GVD, 2019). In the same period 1900–2019, out of the total loss of lives caused by HMHs in Europe, 87.6% was due to extreme heatwave events, followed by flooding (8.7%) and landslides (3.6%) (SI Table S2). During this period, 37.7% fatalities occurred in the seven countries where NBS are being implemented in the OPERANDUM project and 62.3% fatalities occurred in the rest of Europe. In the former case, 32.7% was due to heatwaves, while the other hazards (landslides and flooding) accounted for 5% in total (SI Table S2). In addition to the past damages, the economic loss in Europe is expected to increase from current 14.4 billion USD per year to nearly 88.8 billion USD per year by the end of the 21st century (Forzieri et al., 2016; Hallegatte et al., 2013). Hence, such spatial analyses as those provided here could assist policy-makers at national and EU level in planning and determining the optimal allocation of resources for alleviation measures for HMHs, such as nature-based interventions. This, on the other hand, calls for a proper assessment of the specific type of intervention to be implemented and evaluation of its impacts and merits over the short- and long-term.

4. Indicators for HMH assessment

Indicators are a set of parameters used to define, characterise, evaluate or compare any individual, object or associated processes based on their features or performance of interest. For example,

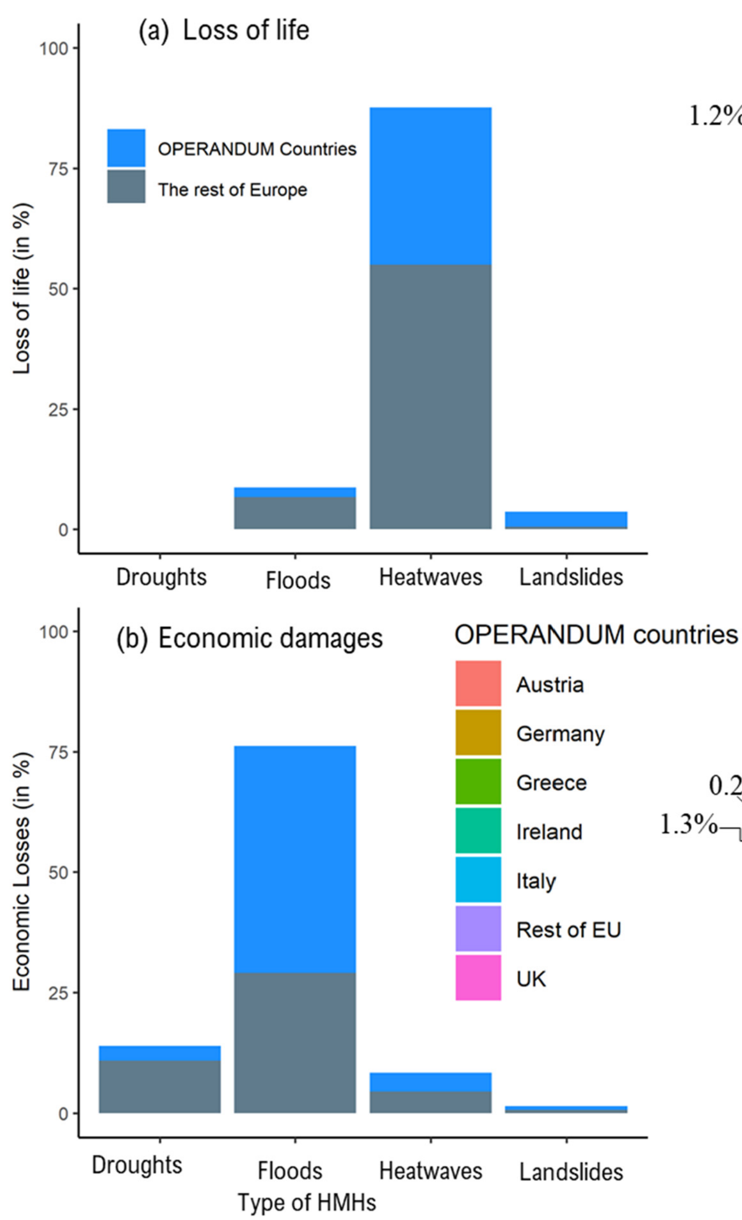


Fig. 2. (a) Distribution of fatalities and (b) economic losses per country and HMHs across OPERANDUM countries and the rest of Europe during 1900–2019 (EM-DAT, 2019).

population socio-economic indicators define various aspects of population, such as poverty, literacy or health. Similarly, HMH indicators, as in the present context, represent HMH characteristics such as its intensity, spatial coverage, frequency, or suitability for its management by various interventions, such as NBS. HMH indicators are generally utilised from a management point of view. There is a growing need to establish such local, regional and national level set of indicators for monitoring HMHs and their management through NBS (Raymond et al., 2017). The Expert Team on Climate Change Detection and Indices (ETCCDI, 2019) has proposed a benchmark reference for internationally agreed indices of climate extremes calculated from daily climatological variables to facilitate comparison and to analyse changes in climate extremes (WMO, 2009). These indicators normally portray the statistical fluctuations of climatological/hydrological variables at a given place and time and thus, give an estimation of the stochasticity of the HMHs occurrence (Eriyagama et al., 2009).

The other sets of indicators relevant for CCA and DRR are climate impact, risk, economic and social indicators (EEA, 2019). The applicability of these indicators depends on the purpose. For instance, progress towards implementation of Sendai Framework for DRR will be monitored via a set of global and national indicators developed by 'open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction' and approved by the UN General Assembly on 2nd February 2017 (UN, 2019), which directly or indirectly can support the operationalisation of NBS against HMHs. Climatological and hydrological indicators can be used as an input (Fig. 3) for scenario and impact analysis based on empirical and numerical models to design suitable, climate-proof, resource-efficient and resilient NBS (e.g. Deak-Sjöman and Sang, 2015). SI Table S3 shows a summary of the most widely used software/models along with relevant forcing data, discretisation (in time and space) which are used to understand, assess, map and predict risk and damage of different HMHs (floods, droughts, storm surge and landslides), and efficiency evaluation of potential NBS against them. For instance, numerical models, such as Flood Modeller Pro (e.g. *Jacobs Flood Modeller: Online Manual*, 2018), LISFLOOD-FP (e.g. Neal et al., 2018), MIKE11 (e.g. Thompson et al., 2017) and HEC-RAS (Hydrologic Engineering Centers River Analysis System; e.g. Guida et al., 2015), have been used in flood risk mapping, damage assessment and simulating the optimal NBS (i.e. retention pond and wetlands to reduce flood risks). Similarly, SWAT (Soil Water Assessment Tool; e.g. Sehgal and Sridhar, 2019), MODFLOW (Modular 3D Finite-Difference Groundwater Flow Model; e.g. Zamanirad et al., 2018), HydroGeoSphere (e.g. Ameli and Creed, 2017) and HEC-HMS (Hydrologic Engineering Centers Hydrologic Modelling System; e.g. Mahmood and Jia, 2019) have been applied for drought risk assessment and management by NBS in different parts of the world. For storm surge and landslides, ADCIRC (ADvanced CIRCulation) model and DEM (Discrete Element Method) respectively are among the widely used models for mapping and assessing risk and evaluating potential NBS. Thus, climate impact indicators can be used to force the scenario and impact modelling in the co-planning phase of NBS operationalisation and support its development and commissioning for managing the projected impact of climate change. Indicators for change in HMHs features due to NBS or, in other words, NBS efficiency ought to be designed at an early stage of the project implementation and respective monitoring should be undertaken. The implication of HMH indicators for the natural hazards discussed below are crucial for planning, designing, and operationalising NBS as a long-term sustainable approach to manage them.

4.1. Floods

Floods are caused by the combination of various meteorological and hydrological phenomena, such as heavy precipitation, hydrological preconditions and runoff generation processes (Debele et al., 2019). Flood indicators can be utilised to estimate the timing, frequency, duration and intensity of any type of flood. A number of indicators have been applied in various parts of the world to describe flood intensity, such as peak flood discharge (Debele et al., 2017b, 2017a; Blöschl et al., 2017), flow depth and velocity (French and Miller, 2011) or flood peak, duration and volume (Ganguli and Reddy, 2013). Using more than one flood indicator could solve the problem of underestimation of flood risk originating from different sources or coincident events (Debele et al., 2017a; Debele et al., 2017b). For example, Wang et al. (2015) applied five comprehensive indicators to evaluate flood intensity: (1) peak flows (annual maximum floodwater discharge); (2) maximum water level (floodwater height in a river); (3) maximum daily volume (maximum amount of water recorded within the first 24 h of a flood event); (4) maximum 3 days volume (maximum volume of water within 72 h); and (5) total volume of floodwater (volume of floodwater that inundates the floodplain). Using these five indicators, flood frequency analysis with any exceedance probabilities of interest (e.g. 100-year return period or exceedance probability of 0.01) can be done. Such indicator-based information can be used for successful design, operationalisation and maintenance of the estimated 100-year design life of NBS projects for flood controls (e.g. sustainable urban drainage systems, urban green spaces).

4.2. Drought

The severity of drought can be analysed based on a combination of three major drought indicators: (1) Standardised Precipitation Index (calculated from cumulative precipitation to detect and describe meteorological drought); (2) Streamflow Drought Index (derived from monthly streamflow using cumulative probability distribution to reflect the intensity, volume and duration of hydrological drought); and (3) Modified Palmer Drought Severity Index (constructed based on the monthly and average precipitation, water supply and demand to characterise agricultural drought or variation of soil moisture). These indicators represent various elements of the water cycle, such as precipitation, evapotranspiration, soil moisture, surface and groundwater levels that are linked with specific types of drought, i.e. meteorological, soil-moisture and hydrological (Sahani et al., 2019). Using these statistical indicators, one can characterise the timing, frequency, intensity, duration and types of droughts which are helpful for planning, designing and maintenance of NBS for droughts (e.g. soil and water conservation measures, water harvesting ponds).

4.3. Storm surge and coastal erosion

The abnormal rise in seawater level during a storm is called storm surge and it is measured as the height of the water above the normal predicted astronomical tide (NOAA, 2020). The surge is caused primarily by a storm's winds pushing water onshore. The dynamics of the storm surge depends upon the sea surface conditions and prevailing wind patterns at various spatio-temporal scales. The barrier between wind and the sea surface generates waves that push the water up and down over the time scale of a few seconds to several minutes to trigger coastal flooding and erosion. Severe coastal flooding and erosion occur when the sea surface is strongly pushed to rise temporarily above mean sea level for several hours or even days. The risk from storm surge can be monitored by various indicators, such as extreme ocean water level (generated by the movement of wind on the ocean surface and fluctuations in the atmospheric pressure linked with storms), exceedance probability of ocean water level (based on statistical distributions to estimate extreme sea levels that occurred once in 100 years or exceeded the probability of 0.01) and changes in tidal levels (the height difference between peak and low tide which can cause the rise and fall of ocean level). These indicators should be considered while designing, monitoring or evaluating sustainable coastal management measures (coastal

Fig. 3. An illustration of key processes (i.e., co-planning, co-design and co-management) involved in the operationalisation of NBS.

wetlands, sand beaches, dunes, concrete seawalls combined with coastal ecosystems such as mangroves and salt marshes) along the coastline (EEA, 2019).

4.4. Landslides

Landslides are mainly triggered by the combination of meteorological, hydrological and geological factors. Rising temperatures and heavy precipitation affect slope stability of rocks, which increases the frequency and intensity of shallow landslides (Alvioli et al., 2018; Huggel et al., 2012). The indicators to monitor the intensity and impact of landslides are mostly derived from extreme precipitation and temperature events which include consecutive wet days (number of days with daily precipitation greater than or equal to 1 mm), maximum daily precipitation and temperature (maximum precipitation and temperature recorded within 24 h) and persistent precipitation (number of days with precipitation greater than 20 mm) (Peres and Cancelliere, 2018). The other two important landslide hazard indicators are landslide displacement rate and groundwater level.

5. Operationalisation of NBS by means of OALs

While the concept of NBS has become increasingly popular and been widely promoted in the last decades, its translation into standardised and well-accepted practices (operationalisation) for HMR reduction and mitigation is still at an early stage. Several factors contribute to hamper the operationalisation of NBS, including the lack of robust and science-based evidence of the effectiveness of NBS for HMHs in current and future climate scenarios, along with ad-hoc tools of communication, as well as know-how transfer mechanisms which can bridge science, community and policy knowledge together. In that respect, OALs might be regarded as a sort of "proof-of-concept" of NBS for HMHs, thus drawing the path for their operationalisation and wider uptake. OAL is a relatively new concept, which has emerged almost in parallel to the popular concept of "living labs" applied in urban scenarios. It combines existing research and innovation processes within a public-private-people partnership and engaging researchers with the community to investigate environmental issues (Davies et al., 2011). In the present context, OAL promotes a user-centric co-design approach where shared knowledge and skills of stakeholders, researchers and end-users are utilised to deploy/demonstrate the effectiveness of NBS to address HMRs (Section 7.1). Thus, OALs could be considered as a benchmark to realise NBS operationalisation as it is established on a set of principles and mechanisms that guide the co-design, co-development, co-deployment and demonstration of the effectiveness of NBS against HMHs. Fig. 3 shows the conceptual diagram for designing and operationalisation of NBS through the inclusion of impact/scenario modelling (research), policy framework (policy) and multi/transdisciplinary stakeholders (practice). The concept of OALs has been recently implemented in seven European countries by the H2020 project OPERANDUM, where it is being used to study and demonstrate the applicability of the NBS for HMHs under both present and future climate change scenarios (SI Fig. S3). Each OAL addresses either a single or multiple interrelated HMHs, hence requiring significantly different NBS approaches and types of intervention. The specific location of these OALs, targeted HMHs, existing and planned NBS during the life cycle of the project and beyond are summarised in Table 3. The geographical location and spatial domain of an OAL depend on a number of factors, such as exposure to the occurrence of HMHs at the high magnitude, presence of high-valued ecological/cultural/strategic elements, aimed targets and the type of NBS interventions envisioned and/or feasible. In the following Sections 5.1–5.4, we further elaborate the concept of OAL through a set of examples and discuss in detail the specific types of NBS that can be operationalised in these OALs for five targeted HMHs (Section 2).

5.1. Flood protection

Current risk reduction measures against flooding of catchments are mostly based on grey approaches, such as dykes, channelization of natural streams, providing culverts under roads and bridges and construction of stormwater detention basins. However, the focus is now shifting towards NBS as a flood control strategy. The OALs, being realised by OPERANDUM project in Germany, Greece, Italy and Ireland, are among the first few examples of operationalisation of NBS for flood risk management (Table 3). In Germany, the OAL concept has been applied at the Biosphere Reserve of Niedersächsische Elbtalaue, a flood-prone area along the Elbe river. Significant floods have occurred in this catchment in 2002, 2006, 2011 and 2013 (Thieken et al., 2005; GVD, 2019). The residual risks include potential damage to assets, dykes, loss of fodder production, disruption of ferry communication and tourism activities. The future projections of flood risk as a result of heavy precipitation in the upper basin of the Elbe and Danube rivers, Germany, revealed an increasing trend for the periods 2011–2040 and 2041–2070 (Bouwer et al., 2010; Jonkman and Vrijling, 2008), thus calling for more systematic and nature-based interventions. In Ireland, the Dodder river catchment gets inundated by flash floods, storm surges and tidal flooding at the downstream part of the river near the estuary. Major flood events have occurred in this catchment in 1986, 2002 and 2011 (Steele-Dunne et al., 2008). Over 300 properties and 66 million USD economic loss have been caused by these floods (Pilla et al., 2019). In Greece, the region of Sterea Ellada faces heavy rainfall and riverbank overflow due to flood water combined with snowmelt in the upstream mountainous areas which cause inundation of the Spercheios catchment from October to May. Spercheios catchment has experienced four extreme floodings in 1993, 1997, 2012 and 2017. In Italy, the Po river basin is a multi-hazard prone catchment, and in particular, in the province of Modena, more than nine severe flood events have occurred over the last 50 years. The most recent and devastating floods occurred in January 2014 when an area of more than 50 km^2 was inundated with an economic loss of more than 550 million USD (Orlandini et al., 2015; Carisi et al., 2018).

NBS, such as ponds, wetlands, constructed wetlands, strips, hedges, shelterbelts, bunds, and riparian buffer can help attenuate flood peaks and enhance free drainage to the river by increasing surface roughness, flood retention time and infiltration into groundwater, thereby slowing down the flooding process (Acreman and Holden, 2013; Dadson et al., 2017; Stratford et al., 2017; Bautista and Peña-Guzmán, 2019). Bautista and Peña-Guzmán (2019) found that increasing green spaces can reduce significant water volume during intense precipitation events in impermeable areas. Thus, NBS can help in decreasing the risk of flooding by reducing flow velocity and destructive powers of flood waves (Moel et al., 2009). Also, improved infiltration procedure slows down runoff velocity as water passes slowly through the soil and helps in slowing erosion tendencies (Collentine and Futter, 2018).

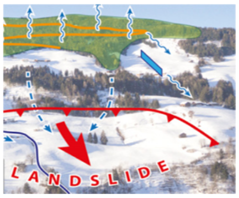
The hybrid approach, such as sustainable drainage systems, bioretention swales and bioretention basins can provide efficient treatment of stormwater by increasing infiltration of rainfall-runoff water and rising groundwater table above normal levels (Water, 2005; Liu et al., 2014; Debele et al., 2019; Sahani et al., 2019). NBS can be also implemented as superficial reinforcement that can help to strengthen the levee/dyke; for example, the installation of herbaceous perennial deep rooting plants can protect the levee from breaching by decreasing its failure probability or delaying the triggering condition of the uncontrolled failure in case of floodwater overtopping (Mazzoleni et al., 2017). Also, sediment basins can be used to retain coarse sediments from rainfall-runoff resulting floods (Water, 2005). The above mentioned four OALs of OPERANDUM project can be used as testing grounds for these co-designed, co-developed and planned NBS against flooding (Table 3) to assess their performance, promote their acceptance and facilitate their adoption in new risk management policies.

5.2. Storm surge and coastal erosion protection

Storm surge induced coastal erosion causes loss of biodiversity, dune habitats and recreation areas. Scotland and Italy are two good examples of countries facing this hazard more frequently. In Scotland, Catterline is a coastal village along the North Sea in Aberdeenshire (SI Fig. S3) where severe hazardous events triggered by heavy/prolonged rainfall and coastal erosion, such as landslides occurred in 1995 and 2012 (Walvin and Mickovski, 2015).

As seen in Table 3, NBS intervention has not been made against storm surge and coastal erosion in Scotland so far and thus, using OAL as a focal point for co-designing, testing and operationalisation of potential NBS are under development. It has been evident that NBS, such as coral reefs, vegetation and wetlands along the coastline can reduce the impact of wave intensity by attenuating wave velocity and reducing the vulnerability of people and assets to storm surge (Arkema et al., 2013). They may provide better protection against storm surge to coastal habitats than hard engineering coastal defences (Bridges et al., 2015). In 2005, hurricanes Katrina and Rita on the Gulf of Mexico coast of the US raised concern over reduced shoreline protection due

Table 3
Table summarising features of OALs of the OPERANDUM project, including their location, HMHs being addressed, and existing and planned NBS (source: OPERANDUM, 2019).

Catchment name	Country	Coordinates		HMHs	Existing NBS	Planned NBS
		Longitude	Latitude			
 Lower Watten valley	Austria	11.6°E	47.2°N	Landslides	Green	Optimising forest management – increase root water uptake and transpiration. Drainage trenches –controlled discharge of surface water and drainage trenches along forest roads. Sealing of streams and channels – prevent infiltration of surface water and replace temporally placed measures. Controlled snow accumulation – controlled snowmelt discharge.
 Lake Puruvesi	Finland	29.5°E	61.9°N	Increased nutrients and sediment loading	Green	Construction of sedimentation ponds and pits, buffer zones, wetlands and peak runoff control structures in the catchment areas and selection/limitation of forest management practices.
 Biosphere Reserve Elbe Valley	Germany	11.5°E	51.5°N	Floods	Green	Reinforcement of decentralized retention areas in the marshland, unsealing areas and land-use changes, re-activating floodplains, re-naturation of embankments.
 Spercheios River	Greece	22.2°E	38.9°N	Floods Drought Floods Drought Floods Drought Floods Drought	Unsystematic	Increasing soil infiltration, potentially reducing surface runoff, by free-draining soil. Planting floodplain or riverside woods. Reducing water flow connectivity by interrupting surface flows, by planting buffer strips of grass and trees.
 Dodder River	Ireland	6.3°W	53.3°N	Floods	Unsystematic	Sustainable Urban Drainage Systems (SUDS), constructed wetlands, riparian buffer areas, buffer zones with several vegetated areas, bio-engineering solutions, promoting practices to reduce water usage.
 Po Valley	Italy	11.5°E	44.5°N	Floods Drought Coastal erosion and storm surge	Unsystematic	Seeding of deep rooting plants, enhancement of biodiversity, filtration strategies to reduce eutrophication and preserve water quality. Promote practices to reduce water usage, promoting alternative crops
 Catterline	Scotland	2.2°W	56.9°N	Coastal erosion Storm surge Landslides	Unsystematic	Eco-engineering solutions to reduce erosion. Enhance the stability of earthworks and natural slopes.

to habitat loss (Stokstad, 2005). The damages during the December 2004 Indian Ocean tsunami were lesser in areas sheltered by coastal wetlands in the form of mangrove forests (Marois and Mitsch, 2015). However, how much and to what extent the mangroves can deliver the protection and what factors control this protection need further investigation. For instance, comprehensive coastal defence programs should not depend on just mangroves, but should also invest in and integrate non-structural measures, such as early warning systems and education (Marois and Mitsch, 2015). Saleh and Weinstein (2016) showed that levees covered by coastal marsh are less prone to damage during the storm surge. Shoreline vegetation barriers act effectively to reduce erosion of coastline by limiting wave height in the range of 0.3–5% (Anderson et al., 2011). Similar effects can be derived from natural coral reefs (Reguero et al., 2018) or the construction of banks of oyster reefs (Bayne, 2017).

Ecological engineering performs a similar function to that of a hybrid NBS to reduce coastal erosion, such as the construction of artificial dunes (Seok and Suh, 2018) or planting vegetation on the natural dunes (Gracia et al., 2018). The grey-engineered infrastructure combined with green approach (vegetation retaining structures) can better resist and dissipate the flood wave energy to mitigate the effects of coastal erosion and storm surge (Vicari et al., 2013; Cousins et al., 2017). Similarly, beach nourishment (Walvin and Mickovski, 2015) and cobble berm construction (Hapke et al., 2006) in the littoral zone can be potential NBS to mitigate after-effects of a storm surge by providing the basis for ecological restoration and stability to the potentially mobile sediment. Thus, it can be concluded that strategic deployment and management of hybrid NBS in OALs near the shorelines can be effective measures to reduce storm surge impacts and associated secondary hazards. For example, OAL in Italy is practising biodiversity restoration, while OAL in Ireland is operationalising constructed wetlands and vegetated or riparian buffer zones (Table 3) for storm surge and coastal erosion protection.

5.3. Drought protection

The basins of Spercheios in Greece and Po river valley in Italy are the two examples of the most drought vulnerable regions in Europe (SI Fig. S3) and hence provide the opportunity for applying the OAL approach for NBS. Spercheios river catchment is specifically experiencing hydrological and socio-economic drought. The existing mitigation measures in Spercheios river catchment area focus mainly on actions to (a) increase water availability, (b) decrease water demand, and (c) mitigate drought impacts. The description of these two catchments was discussed in Section 5.1, and the list of planned potential NBS (green/blue/hybrid) against droughts is given in Table 3. NBS interventions, such as soil conservation (e.g. crop rotation, cover crops) and connectivity of the landscape (i.e. increase infiltration or reducing surface runoff by making the landscape less connected) can restrict soil moisture/agricultural droughts (Masselink et al., 2017; Keesstra et al., 2018). At the catchment scale, a wetland can reduce the connectivity in the riverine system, limiting runoff and increasing water availability for agriculture (Keesstra et al., 2018). An excellent example is provided by the "agro-silvo-pastoral systems" in southern Portugal, also known as "Montado" in southwest Spain. These systems are designed and deployed based on ecological engineering (hybrid NBS) for sustainable water supply and vegetation productivity and can increase the resilience to droughts (Keesstra et al., 2018). They are self-maintained systems with a minimum of human work input, characterised by the dispersion of open oak formations, olive and chestnut trees associated with animal grazing and cultivation (Pinto-Correia, 1993). Ectomycorrhizal fungal community is found in abundance in Montado systems which is effective in increasing the resilience of the managed system to drought due to the lower competition for water and nutrients (Azul et al., 2010).

A combination of 'grey-green-blue' or hybrid solutions is an innovative approach that links water management and green infrastructure to maintain a natural water cycle and enhance environmental and urban renewal (Drosou et al., 2019; Krauze and Wagner, 2019). The combination of 'grey-green-blue' includes ditches, vegetation, lakes, ponds and wetlands. For instance, the hybrid approach in Augustenborg, southern Sweden, improved water availability and decreased droughts (Keesstra et al., 2018). Table 3 shows the list of potential NBS against droughts which are planned in two OALs of Greece and Italy (OPERANDUM, 2019).

5.4. Nutrients and sediment loading protection

Activities related to forestry along with heavy rainfall can increase concentration of nutrients (i.e. nitrogen and phosphorus) and suspended sediment loads to the recipient water bodies and further deteriorate water quality. For example, many parts of the sub-catchments of Lake Puruvesi and Vehka-Kuonanjärvi in eastern Finland (SI Fig. S3) are affected by eutrophication caused by the excessive richness of nutrients. In 1998 and 2012, the hazard caused loss of aqua flora and fauna, and alteration of coastal zone vegetation (EEA, 2019). NBS, such as sedimentation ponds, pits, submerged dams, constructed wetlands, riparian buffer zones and peak flow control structure are able to capture eroded suspended solids and particulate nutrients released from the active forest management area before they enter the receiving water body (Marttila and Kløve, 2010; Nieminen et al., 2018). Their efficiency depends upon their ability to reduce the flow velocity and retain dissolved nutrients by biological and physiological processes (Finer et al., 2018). Marttila and Kløve (2010) indicated that peak flow control structures can decrease the velocity of the flow up to 91% and the suspended solids up to 86% in Finland. The most efficient NBS appears to be constructed wetlands and overland flow areas or wetland buffers (Marttila and Kløve, 2010). The vegetation and micro-organisms growing in the constructed wetlands use soluble nutrients directly from the water and bottom sediment (Vymazal, 2008).

A study conducted in a forested catchment of Finland using two constructed wetlands showed that over 80% of the suspended solids were retained but nutrient retaining was less efficient (Joensuu et al., 2013). Overland flow areas retain nutrients through biological accumulation in wetland vegetation and chemical adsorption by the soils (Nieminen et al., 2018); efficient retention of dissolved nutrients has been observed especially after transient high nutrient loadings (Väänänen et al., 2008; Vikman et al., 2010). In addition to the above mentioned NBS, it is possible to control sediment and nutrient load with forest management regimes by leaving adequate riparian buffer zones between water bodies and tree cutting areas which reduce erosion and water load. Also, it is assumed that less nutrient and sediment leaching occurs by using 'continuous-cover-forestry' compared to 'clearcuttings' because the forest is covered with vegetation all the time in the earlier regime. To test and demonstrate their effectiveness, the types of planned NBS against nutrients and sediments in OAL of Finland are summarised in Table 3.

5.5. Landslide protection

Landslides are a major hazard causing significant fatalities and economic loss, e.g. in Austria and Scotland (Section 5.2; SI Fig. S3). The landslide in the lower Watten valley is an active sub-system of a deep-seated gravitational slope deformation (DSGSD) located in the Tuxer mountain range in the state of Tyrol, Austria. The whole slope ranging from 750 to 2000 m above mean sea level and covering an area of about 5.5 km^2 has been repeatedly active in terms of movement at least since the last glacial maximum 22 ka ago. Currently, a sub-system of the DSGSD in the lower part of the slope shows enhanced movement with mean displacement rates of about 3 cm/a. The 3.5 years' displacement time series derived from an automatic tracking of the total station shows phases of acceleration and deceleration correlating with moist periods of above-average precipitation and enhanced infiltration of melted water during snowmelt. The current active area of about 0.25 km^2 is covered by agricultural land including meadows, pastures and local forest patches. Green NBS were implemented in OAL-Austria in the past, but other types of NBS are also being planned using the OAL concept (OPERANDUM, 2019), as summarised in Table 3.

The potential NBS against landslides include soil bioengineering measures, cultivated slopes and restoration of susceptible or already failed slopes. These measures can provide an effective alternative or additional support to hard engineered solutions (Stokes et al., 2014; Rey et al., 2019). However, the applicability and effectiveness of these NBS depend on the type of landslide. Several studies have shown that green approaches, such as plant roots can efficiently increase a slope's stability (Moresi et al., 2019; Schwarz et al., 2010; Wu et al., 1979; Wu, 2013). The selection of suitable vegetation species and its spatial distribution for stabilizing a particular slope depend on its characteristics including topography, the involved material and the hydrological conditions (Gonzalez-Ollauri and Mickovski, 2017; Roering et al., 2003; Schwarz et al., 2012). The most effective NBS against shallow landslides is reintroducing vegetation cover on a slope together with hard structures, such as live fascines or crib walls (Faucon and Lambers, 2017; Stokes et al., 2009). The other NBS against landslides are cropland and forest management practices, road design and the management of streams and rivers with respect to their hydrological effects (Dhakal and Sidle, 2003; Dolidon et al., 2009). Soil and water conservation measures in hillslopes to collect surface water are also potential NBS which prevent soil erosion and formation of landslides (Popescu and Sasahara, 2009). In conclusion, NBS such as optimising forest management, drainage trenches, sealing of streams and channels and controlled snow accumulation (for specific typologies, see Table 3) can be operationalised in OALs against landslides.

6. Policies for the operationalisation of NBS

European policies have played a leading role in funding and advocating the implementation of NBS as the first line of defence against HMRs in different climatic conditions and regions. However, the practical opportunities in the policy-making process need to evolve for enhancing coherence between the above-discussed HMRs and NBS. Hence, policies for NBS operationalisation are provided here covering relevant ongoing and past legislation and policy frameworks, gaps, barriers and possible ways to overcome them throughout the life cycle of NBS projects (before and beyond the project implementation phases). This can enhance the coherence between science, policy and NBS practice.

6.1. NBS related policies for HMHs

The need for science and policy integration for NBS to manage HMRs is being acknowledged worldwide. For example, the Hyogo Framework for Action (HFA) 2005–2015 (UNISDR, 2005) was an international agreement under the auspice of the United Nations International Strategy for Disaster Reduction (UN-ISDR) which aimed to reduce the loss of lives, economies and properties from natural hazards (Quevauviller and Gemmer, 2015) and thereby making nations and communities sustainable (Quevauviller, 2011). In the HFA, the lack of quantitative data made the monitoring progress of DRR difficult (UNISDR, 2011). To address this issue, recently international policy agendas for DRR, such as Sendai Framework for Disaster Risk Reduction (SFDRR) 2015–2030 (UNISDR, 2015) and the Paris Agreement (UNFCCC, 2015) were introduced with further efforts to measure the DRR progress more effectively. The HFA had very little reference to any nature/ecosystem-based approaches for DRR as opposed to its successor SFDRR which was endorsed by the UN General Assembly following the 2015 third UN World Conference on Disaster Risk Reduction (WCDRR) with the goal of building the resilience of nations and communities to disasters. In this agreement, the policymakers have committed to decrease disaster damages by 2030 and have recognised the main role of measuring disaster losses in achieving this (UNISDR, 2015). The SFDRR has a global agenda of reducing and averting disaster risks by reinforcing adaptation in society and economic settings. It believes that DRR responsibility should be shared among various state stakeholders including local government, the private sector and others. The SFDRR works in parallel with the other 2030 Agenda agreements, including the Paris Agreement on Climate Change, the Addis Ababa Action Agenda on Financing for Development, the New Urban Agenda, and ultimately the Sustainable Development Goals. Other examples include three policy frameworks embedding developments in water-related hazards in Europe are (1) the 'Water Framework Directive', (2) the 'Flood Directive', and (3) the 'Water Scarcity and Drought Communication' make the gist of a European action plan against such hazards.

Water Framework Directive is a European framework legislation that established integrated water resource management principles at its core (European Commission, 2000). Chave (2001) highlighted that these principles were applied in a holistic manner considering risk categorisation, water resources follow-up and river basin management action plans. This directive includes traditional risks, i.e. water overuse or it's quality degradation, and considers all the water bodies (surface and groundwater) and actions that deplete them. Proper measures had to be carried out to achieve the planned objective by 2015. In the Water Framework Directive, HMRs such as floods and droughts were not explicitly discussed but instead addressed through river basin management plans. Therefore, this directive allows for building a strong integrated water resource management network in Europe and provides a background practice for HMRs management under climate change policy outlined in European Commission (2009).

Flood Directive is a European member states' policy for flood risk management which aims to alleviate the flood consequences on human health, environment and pivotal economy in Europe (European Commission, 2007; Gemmer et al., 2011; Djordjević et al., 2011). The Flood Directive is aligned with the application of the Water Framework Directive in watershed management strategy. It therefore gives an inclusive system for evaluating and monitoring increased risks of flooding due to global warming, and for developing proper remediation strategies (Quevauviller and Gemmer, 2015).

Water Scarcity and Drought Communication is a policy framework to manage the increased frequency and intensity of drought risks due to climate change across Europe (European Commission, 2007). Following this legislation, the European Commission evaluates options for tackling the problems of water scarcity and associated droughts in Europe annually (Quevauviller and Gemmer, 2015).

European and international policies for implementing and monitoring the effectiveness of NBS are crucial throughout the life cycle of the projects. We analysed and present the current policies and legislations associated with NBS implementation against HMHs in Table 4. The extent of reference to or mentions of specific HMHs and their respective NBS (Table 4) was found to vary among the documents while reviewing relevant frameworks, protocols, guidelines and policies from 2000 to 2019. Only 34% of the relevant policies directly referred to NBS, while half of them (50%) only contained a weak to moderate reference. The remaining 16% did not refer to NBS at all. This is partly because most policies were developed when NBS was still a poorly understood concept or not yet fully formulated and utilised against HMRs. Almost all recent documents do contain a reference to NBS. Based on these observations, most of the improvements in terms of contributions to the NBS mainstreaming and synergisation can be made in the documents and guidelines that already focus on a specific HMRs, but do not yet refer to NBS as a way of reducing disaster risks. This would be a relatively simple but effective update and improvement to older guidelines/policies utilising the most recent scientific recommendations and technical innovations.

6.2. The mainstreaming of NBS in policy databases

The concept of mainstreaming, which here refers to the additional consideration of adaptation measures to manage climate-related risks, such as NBS in policymaking and implementation, was introduced in 1997 (Collier, 1997). The origin of the mainstreaming concept has its roots in environmental policy framing (Van Asselt et al., 2015), specifically focusing on climate. In recent years, adaptation mainstreaming has become increasingly relevant and necessary for policy and practice (Ojea, 2015; Van Asselt et al., 2015; Wamsler and Pauleit, 2016; Wamsler et al., 2017; Runhaar et al., 2014). By expanding the focus from resisting or preventing hazards to a wider range of adaptation

Table 4
Overview of selected major European protocols, frameworks, guidelines, action plans and policies (2000–2019) regarding NBS for HMR reduction, environmental management and CCA. In terms of focus on a specific HMR: NA = no mention of HMR; 0 = no focus on one specific HMR and no mentioning of NBS to what extent it refers; − = weak or indirect reference to NBS; + = moderate reference to NBS; ++ = strong reference to NBS.

European legislations	HMHs	Links to NBS	Reference
Action Plan ON the Sendai framework	0	++	European Commission (2016)
Key European action supporting the 2030 Agenda and the Sustainable Development Goals	0	++	European Commission (2013b)
The European Strategy on Green Infrastructure	0	++	European Commission (2013a)
The European Strategy on adaptation to climate change	NA	++	European Commission (2013b)
The Water Framework Directive (2000/60/EC)	Floods, droughts	0	European Commission (2000)
The Groundwater Directive (2006/118/EC)	NA	−	European Commission (2006)
The Floods Directive (2007/60/EC)	Floods	−	European Commission (2007)
Common Implementation Strategy for The Water Framework Directive (2000/60/Ec) and the Floods Directive (2007/60/EC)	Floods	+	CIS-WFD (2007)
Strategic Environmental Assessment Directive (2001/42/EC)	Droughts	0	European Commission (2001)
Marine Strategy Framework Directive	NA	+	European Commission (2008)
2012 Blueprint to safeguard Europe's water resources	NA	+	European Commission (2012)
Roadmap to a Resource Efficient Europe	NA	+	European Commission (2011b)
European Biodiversity Strategy to 2020	0	+	European Commission (2011a)
The ICZM Protocol	Floods, droughts	−	UNEP/MAP/PAP (2008)
The Barcelona Convention	Storm surge and coastal erosion	0	European international agreements (2010)
United Nations Convention to Combat Desertification	Droughts	−	UNC (1977)
European Work Programme 2018–2020: 12. Climate action, environment, resource efficiency and raw materials	0	++	European Commission (2019)
European Biodiversity Strategy	0	++	European Commission (2011a)

measures, it seeks to increase sustainability and resilience (Wamsler and Pauleit, 2016; Wamsler et al., 2017).

European and international policies, especially regarding HMRs, play a crucial role in the mainstreaming and synergising of NBS worldwide. It contributes by promoting innovation in sector-specific policies, linking and aligning sector-specific funds and SDGs, and encouraging more efficient use of human, physical and financial resources (Lafferty and Hovden, 2003; Adelle and Russel, 2013; Rauken et al., 2015; Runhaar et al., 2014; Dewulf et al., 2015; Persson et al., 2015). In 2015, several major international UN agreements were signed that work on the implementation of the SDG (https://www.un.org). All were significant for the promotion and implementation of NBS (e.g. Goals #3, #11 and #15). These included the 2030 Agenda for Sustainable Development (UNDP, 2015), the Sendai Framework for DRR (UNISDR, 2015) and the Climate Change Agreement, also known as the Paris agreement (UN, 2015). For example, three of the four priorities of Sendai Framework for DRR directly and/or indirectly support NBS implementation, foster its wider uptake and link them with policies and land regulations. The overarching framework of the 2030 agenda for sustainable development also links the DRR and CCA targets and commitments with poverty alleviation, economic growth, societal participation and environmental protection, and thus supports NBS implementation indirectly. The Paris agreement supports the implementation and promotion of NBS by using an ecosystem approach to combat climate change at the global level. These frameworks perform not only individually but are significantly intertwined and they recognize and support each other. For instance, the Paris agreement contributes to SDG (Goal #9) by reducing and adapting to the adverse impacts of climate change and build long-term climate change resilience in cities and societies. Other examples of policies for mainstreaming NBS on a global level include the UN Sustainability Framework (UN, 2019), Global Framework for Climate Services (GFCS, 2019) and United Nations Framework Convention on Climate Change (UNFCCC, 2019).

While some NBS for HMR reduction have been implemented through pilot projects in different parts of the world, wider uptake of the NBS is yet to be adopted in national and international policies and practices. Recent literature has suggested that a major bottleneck which hindered the wider uptake and acceptance of NBS was lack of principles, standards and guidelines (Renaud et al., 2016). However, some studies have begun to address this gap. For example, IUCN endorsed an eight set of principles on NBS developed by Cohen-Shacham et al. (2016), the five qualification criteria for Ecosystem-based Adaptation (EbA) proposed by Friends of EbA (FEBA, 2017), the seven voluntary guidelines published by the SCBD (2019) and comprehensive guidance for the implementation of NBS proposed by the World Bank against flood risk (World Bank, 2017). The SCBD (2019) recently released its guidelines for EbA and Eco-DRR with a set of six so-called overarching considerations (a series of steps for planning and implementing EbA and Eco-DRR), ten principles and nine types of safeguards. The main ideas of these principles are closely interrelated and partially overlap, but they are relevant to accelerate the wider uptake and acceptance of NBS globally because they address knowledge gaps and provide clear guidance to decision-makers to plan for and operationalisation of NBS in the context of CCA and DRR.

6.3. Synergy between science, policy and practice to improve the uptake of NBS

There are a number of studies advocating for the mainstreaming of NBS as CCA and DRR measures to encourage synergies across research and policy/decision-making processes (Daily and Matson, 2009; Daily et al., 2009; Ojea, 2015; Pasquini and Cowling, 2015; Runhaar et al., 2018). Despite these studies, NBS approaches are still not fully systematically implemented (Nalau and Becken, 2018; Runhaar et al., 2018). Designing and evaluating NBS and their benefits are therefore vital to ensure the consideration and implementation of these services throughout policies and sectors (van Ham and Klimmek, 2017) in decision-making. Wamsler et al. (2017) highlighted that weak or fragmented synergies between science, policy and practice could be seen in the struggle of many end-users and municipalities in shifting their paradigm towards NBS. To address this problem, Wamsler et al. (2017) designed an integrated framework for adaptation to mainstream climate policy, CCA and DRR. Their framework was empirically designed and validated between 2003 and 2016 by cooperating closely with 'governmental and non-governmental organizations' in developed and developing countries. The application of their framework proved to be very effective and helped the municipalities and local communities/citizens in the identification of numerous gaps and ways forward that can bring the concept of NBS from theory into practice. Systematic mainstreaming could produce a strong synergy by fostering creation and co-creation processes across policies, connecting and harmonising adaptation aims, and inspiring more effective utilisation of manpower and economic resources (Rauken et al., 2015; Dewulf et al., 2015; Runhaar et al., 2018).

Building strong evidence and considering NBS as the main adaptation measure among science, policy and practice can thus address the root cause of risks and promote sustainable growth (Ojea, 2015; Wamsler et al., 2017). The successful implementation of NBS at any spatial scale of interest requires strong integration of numerous local, national and international policy/decision-making processes (Section 6), which is challenging to achieve within a short timescale (Rizvi et al., 2015; Runhaar et al., 2018). The preference for "fast solutions" hinders the competitiveness of NBS against grey approaches, which generally are considered more achievable within a shorter time frame. As a consequence, government officials and/or decision-makers tend to support the application of the grey approach for CCA, in lieu of financing in NBS (Rizvi et al., 2015). Thus, to convince and foster the uptake of NBS, in spite of the time requirements, more tangible evidence on the economic benefits, monitoring by field measurement and key performance indicators (KPI) are needed to demonstrate the multiple benefits NBS can provide in both short- and long-term (Rizvi et al., 2015; Runhaar et al., 2018). The other fundamental tool to improve the consideration of NBS in policy-making process and practice is the engagement of citizens and organizations throughout the life cycle of NBS projects (before and beyond the project such as planning, designing, execution, monitoring and evaluation phases) which creates trust, ownership and stewardship among them (Section 7). In that respect, the operationalisation of NBS through OALs may represent an effective way to enhance coherence between NBS and relevant policy frameworks, as it inherently attracts citizens from different backgrounds, while supporting the policy targets mentioned above. OALs seek to combine ecologists with social activism and put a high priority on engagement, sharing and developing common strategies towards NBS. Thereby, OALs contribute to promoting the wider acceptance of NBS through raising awareness, empowering citizens and establishing links between policy and practitioners. In addition, OALs contribute to accelerating stable transformations by disseminating nature-based perspectives and while doing so, it establishes the framework for strengthening NBS policies based on participatory approaches (i.e., that employ transdisciplinary approaches/inclusive partnerships and local communities) (Section 7.1), which in turn, helps to modify policies/institutional regulations related to adaptation measures against HMHs. Overall, the wider uptake and upscaling of NBS would require political commitment, long-term funding and technological development with greater acceptance of the stakeholders. OALs can play an important role in driving end-users' engagement, commitment and acceptance, at least at the local level, as it embraces a user-driven philosophy (Section 7.1).

7. Practicality in operationalisation of NBS

In order to improve the confidence and competence associated with the practicality of NBS, more interdisciplinary research and targeted implementation enterprise are critical. In this regard, some studies recognised that lack of acceptance of NBS can hinder the wider uptake of NBS in practice. As an example, gaps exist between modellers and the public at large as models are often built with assumptions without the direct involvement of stakeholders (Olsson and Andersson, 2006). Therefore, application of NBS into practice requires a strong integration of stakeholders from different sectors (science, policy and practice) to set a solid evidence base, such as the multiple benefits NBS provide and their cost-benefits. This will bring broader support for NBS over the traditional approach and enhance their wider uptake by the end-users.

7.1. Co-design, co-development and co-deployment of NBS with OALs stakeholders

Inter- and trans-disciplinary research, collaboration among researchers and involvement of stakeholders are increasingly seen as good practise to design and operationalise NBS (Nesshöver et al., 2017; Alves et al., 2018). These practices, termed as 'co-approaches' such as 'co-design', 'co-development' and 'co-deployment' of NBS are based on an extensive stakeholder mapping, in-depth analysis, interaction and engagement strategies (Woods-Ballard et al., 2015). For example, researchers from the OPERANDUM project (OPERANDUM, 2019) conducted a comprehensive stakeholder analysis involving end-users, investors, fundraisers, policymakers, designers, delivery and maintenance bodies and suppliers (Fig. 4). They identified specific keywords (coarse and secondary level) for searching stakeholders (SI Table S1) and mapped them at seven OALs after classifying them into various groups, such as primary/secondary or local/national/global (Fig. 4) (Kumar et al., 2019). The type, number and role of the stakeholders vary among the spatial levels (i.e., local/national/global), geographical context (i.e. urban/rural, small scale/large scale) as well as NBS specific types (i.e. technology/method applied). The identified stakeholders (SI Fig. S4), were validated/integrated by the consortium partners during internal brainstorming meetings. The stakeholders are brought together in an interactive co-creation process (from co-designing the project up to the dissemination) combining elements of design and system thinking, continuous reflection and monitoring (Fig. 5).

Due to the popularity of the transdisciplinary approach, there are already experiences of success and failure factors in such processes in various contexts (Lang et al., 2012; Schäpke et al., 2018; Djenontin and Meadow, 2018). The following challenges are faced in the co-design/co-development approach of NBS in OALs (OPERANDUM, 2019). The *attitudes* of the stakeholders (landowners or a government body) not only reflect their behaviour in various phases of the process, but also the overall acceptance of NBS, thus there is a need for awareness of stakeholders' *attitudes* (Santoro et al., 2019). Conflicting *interests* (e.g. economic vs. environmental interests) are mentioned as an issue similar to other environmental management and nature conservation projects (Waylen et al., 2014; Kabisch et al., 2016). For example, in the case of agriculture and forestry, where the short-term economic gains may have a conflict with the environmental goals. Stakeholders' attitudes or interests are not necessarily always connected to their position or role in the value chain, but they may also reflect their wider environmental knowledge about acceptance or denial of climate change, ignorance of the NBS co-benefits, previous experiences of collaboration in similar types of projects, some emotional aspects such as fear of something new or economic risks, or lack of information and understanding about the aim of the project or the NBS (Kabisch et al., 2016; Nesshöver et al., 2017; Santoro et al., 2019). Although attitudes tend to endure, they are not necessarily rigid and can be affected by new information or experience and transdisciplinary research process. Co-creation approach can provide a platform for learning and changing such attitudes (Jahn et al., 2012).

Trust is also an important element that may enable or disable a successful design and implementation of NBS (Hair et al., 2014; Ashley et al., 2015). Trust acts both as a condition for and a result of co-creation. There might be trust or mistrust, due to previous projects and collaboration or science in general (van Ham and Klimmek, 2017). Therefore, it is important to give access and voice to different participants, take into account their values and needs, and take care of transparency of the process to build trust (SCBD, 2019). Planning of NBS may require a long-term (even some years) *commitment* in the process which may be restricted due to resources (time and funds) and social capabilities of the stakeholders (Scholte et al., 2016). In some cases, the participation can be restricted due to *complexity* (technological aspects requiring special expertise and understanding of the terms) or

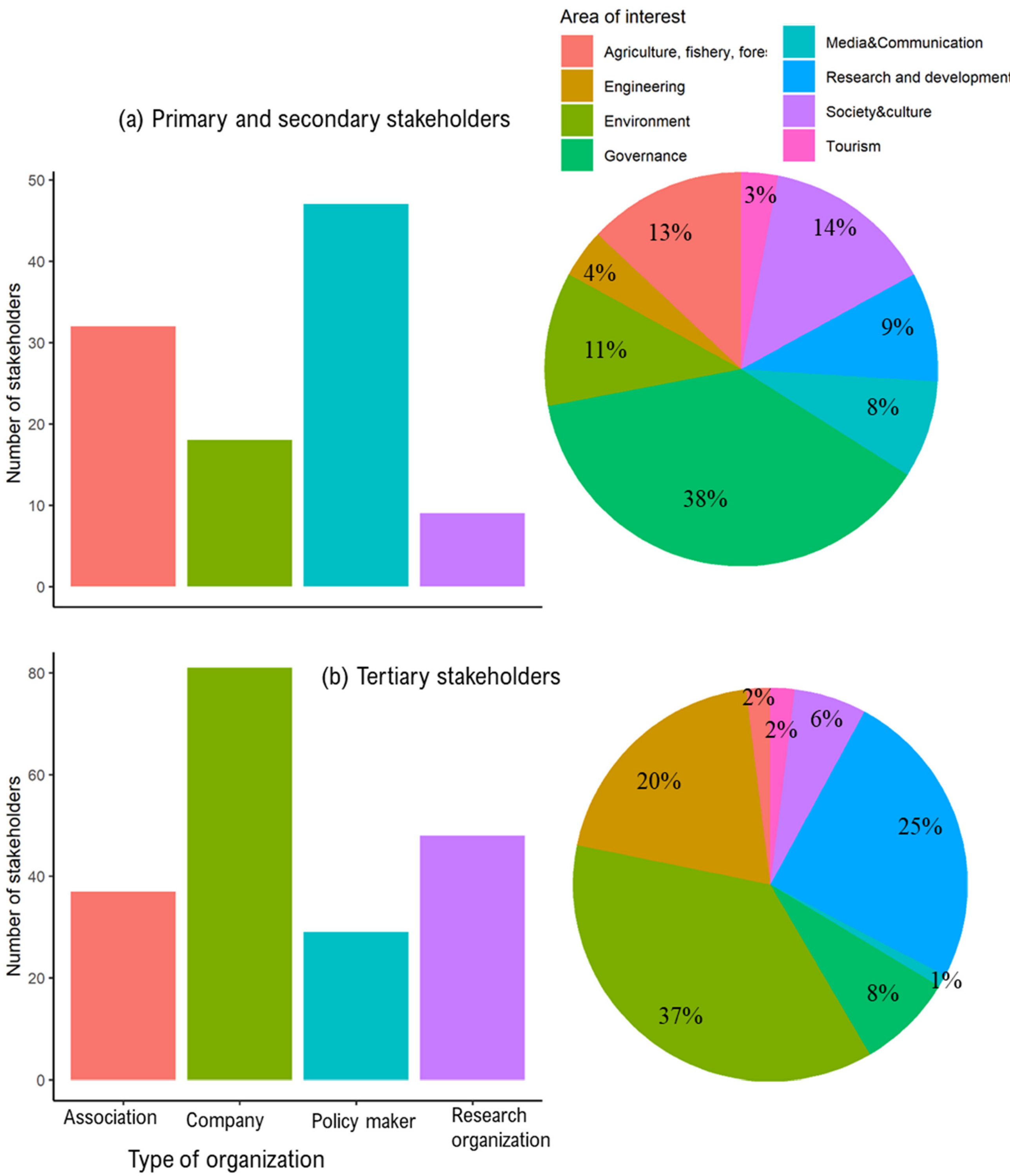


Fig. 4. Mapping of stakeholders: (a) primary and secondary stakeholders; and (b) tertiary stakeholders at seven European country level.

the *physical environment* of the planned NBS (difficult to reach or dangerous work).

Despite these challenges, it is important to engage different stakeholders as it is generally assumed that diversity of knowledge in the design and implementation of NBS, similar to any other environmental management or planning situation, would lead to more sustainable and legitimate solutions (Durham et al., 2014). Moreover, the exchange of knowledge between the experts and practitioners may lead to learning and long-term capacity building. Different types of knowledge that are brought together are scientific, local and traditional knowledge to create understanding regarding the current social-ecological system, scenarios of the future including the knowledge and perceptions of the risks. Therefore, integration and governance of knowledge (Tengö et al., 2017; van Kerkhoff and Pilbean, 2017; Cohen-Shacham et al., 2019) during the co-creation process need special care as these involve several issues from different types of expert knowledge (technological and social). In these situations, issues of power and questions like what knowledge is valid and whose knowledge is accounted for are

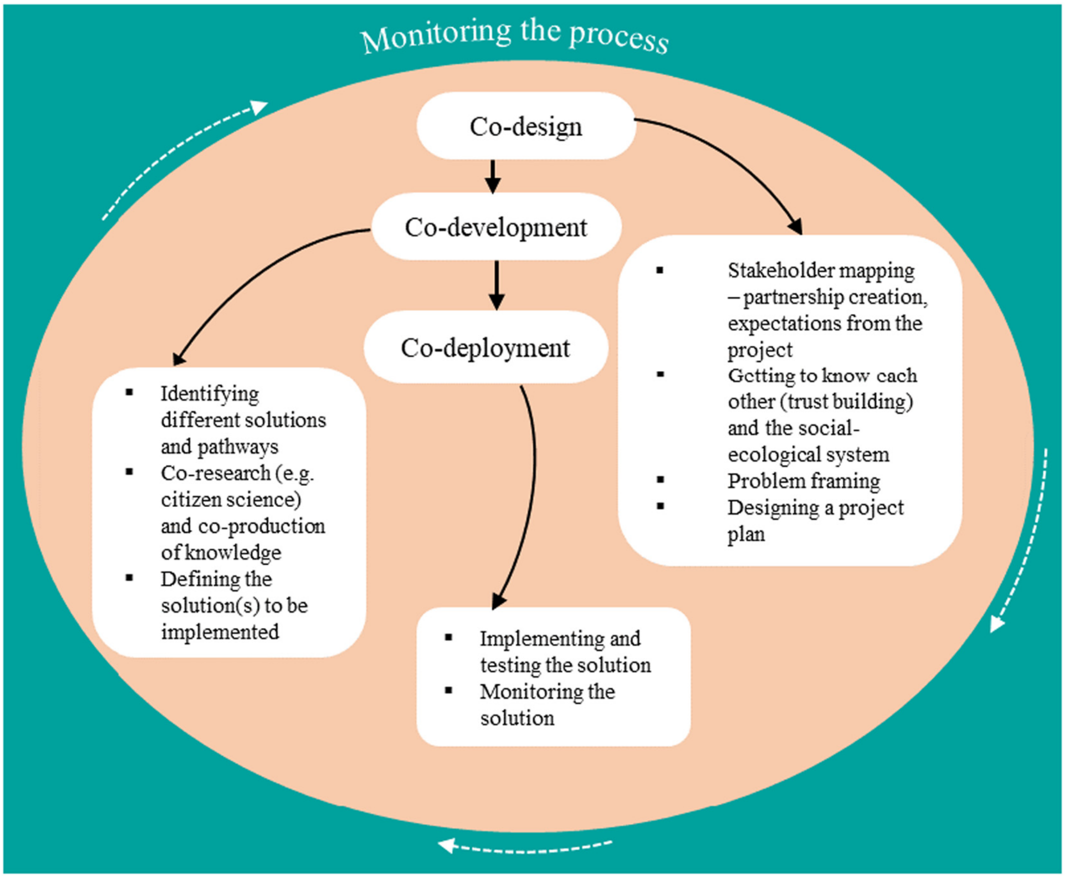


Fig. 5. Types of stakeholders' involvement in the co-designing process of NBS operationalisation.

always present (Montana, 2019). The scale and diversity of the social-ecological systems, the variety of stakeholders involved, the uncertainty related to the assessment of HMRs and the efficiency of the planned solutions bring additional taste in these co-creation processes of NBS.

7.2. The need for NBS performance standards

European governments invest billions of euros to address the challenges faced in their territories. Off late, a growing number of projects are focusing on NBS in Europe (Table 1) but their long-term effects and cost-effectiveness for HMR reductions are just at the initial stage of the investigation. To assess the efficiency and effectiveness of the NBS, their performance in terms of socio-ecological benefits should be monitored for compliance with the design brief.

In the absence of specific NBS design standards, the existing European engineering standards (e.g. Eurocodes for civil engineering) can be used for design and specification of the 'hard' or structural parts of the NBS structures. These can be enhanced with the addition of specifications and protocols relating to the 'green' or environmental parts of the NBS. All of these assessed throughout all of the stages of an NBS project will contribute to both the stability and sustainability requirements to be incorporated into the life cycle of an NBS. To achieve this, a conceptual framework (Mickovski and Thomson, 2017) based on a set of sustainability KPI can be developed (Fig. 6) and is currently being used by OAL Scotland (see OPERANDUM, 2019). Therefore, scientifically proven methods or tools are required to monitor/measure the long-term performance potentials of NBS. This will help to analyse costs and benefits over time, and integrating the evidence thus gained into management plans and policy instruments. As a result, there is a real market opportunity for NBS and the public administration is beginning to invest in it instead of the classical solutions to tackle different HMRs (Talberth et al., 2013).

7.3. Barriers and data gaps for NBS implementation

The discussion in Sections 7.1 points out that the process of co-design and co-development of a specific NBS has multifaceted challenges, such as the assessment of the specific HMH and related risk that a certain location is facing over time and space, the identification of ad-hoc NBS interventions based on the geographical, political and environmental characteristics of the site, the degree of social/cultural acceptance, the assessment of the NBS cost/benefit ratio and related market opportunities as well as the provision of tangible results through accurate and systematic monitoring protocols.

Each of these aspects requires specific environmental and/or socio-economic datasets (geospatial and non-geospatial) as input to be properly assessed. On the other hand, the same is also true in terms of output, since the effectiveness, impacts and degree of replication of a certain NBS needs to be evaluated and monitored over time through quantifiable, objective and scientifically sound indicators (output), whose computation strictly relies on the availability and adequacy of environmental and/or socio-economic datasets of various types.

The availability and adequacy of data, therefore, represent one of the "hidden" challenges in the process of NBS acceptance and assessment and may impede its successful operationalisation (and widest uptake) as long as common, well-established and documented practices and metrics of NBS evaluation and monitoring are missing. Strictly related to the above, it is also the issue of data discoverability in the context of NBS.

Nowadays, a vast amount of data (geospatial and non-geospatial) are easy to search and made available on the internet. Non-geospatial data are usually searchable over the web while geospatial data are often stored in databases or a filesystem, and served through standard web services defined by the Open Geospatial Consortium (OGC). These data are usually ignored by search engines and thus are not

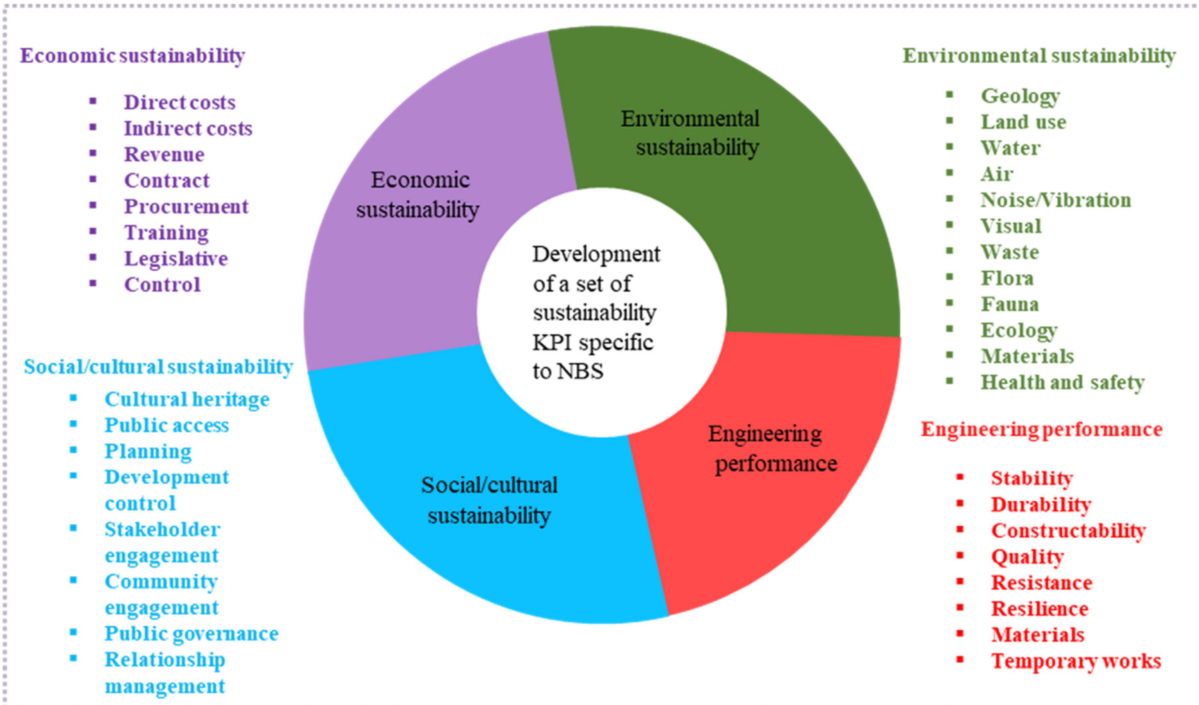


Fig. 6. Conceptual design of a sustainability framework which will include the engineering performance of the NBS; adapted from Mickovski and Thomson (2017).

discoverable in the mainstream web which reduces the possibility for wider usage of such data. Catalogue (discovery) service enables describing data with a set of metadata to facilitate their easier discoverability and usability (Köhler et al., 2006; Tzotsos et al., 2015). Catalogue service is often used as a gateway from the web to geospatial data. Also, catalogue services are often used within the implementation of Spatial Data Infrastructure (SDI) to facilitate discovery and use of geospatial data (Shvaiko et al., 2010). Data properly described with a set of standard metadata elements such as those described in ISO 19115 allow easier assessment of data adequacy and data appropriateness (Pinardi et al., 2017) for machines following semantic web concept (Berners-Lee et al., 2001; Egenhofer, 2002). It is therefore essential to make NBS-related data compliant to these standards. This also calls for the introduction of additional or newly created metadata elements for properly tagging the NBS concept and enabling easier discovery of NBS data.

8. Conclusions and future outlook

This paper focused on the operationalisation and the wider acceptance of NBS for managing HMHs. It provided a comprehensive review on its implementation processes incorporating HMH trends, relevant policies and strategies and the limitations confronted for their advocacy. The mechanism of NBS operationalisation was analysed and presented in detail for five different HMHs (floods, droughts, landslides, coastal erosion and storm surge, and nutrients and sediment loading) and further exemplified through the experience of seven EU-OALs. Historical and projected trends in HMHs, damages caused by them (i.e. economic damage and loss of life), and indicators needed for their assessment were evaluated for each hazard category, and the importance of their knowledge in the process of NBS designing and operationalisation was discussed. To ease and guide the planning and designing of NBS projects against HMRs, a variety of specific NBS types and interventions was then scrutinised for each type of HMH, highlighting both gaps in knowledge and potential benefits. The review of existing literature, past and ongoing NBS projects, along with the analysis of the European policy frameworks applicable to HMR management through NBS, clearly pointed out the need for synergy between research, policy and practice, and that co-design and co-development of NBS for HMRs should be carried out in a transdisciplinary, multi-stakeholder and participatory context. The review resulted in the endorsement of certain provisions and data lacking for the needed advancement in NBS implementation.

The following conclusions are drawn:

- Over the last three decades, Europe has been impacted by HMHs such as floods (particularly central, northern and eastern Europe) caused by heavy precipitation, as well as heatwaves and droughts (southern and western Europe) caused by long-lasting conditions of high temperatures and low precipitation. In the period 1980–2017, the reported economic losses caused by climate-related hazards in the EEA-33-member countries amounted to 618.5 billion USD; out of those, approximately 502.56 billion USD losses were specifically caused by weather and climate-related extreme events. Among the reviewed HMHs, heatwaves and floods caused significant loss of life and economic damage across Europe. The occurrence of floods is expected to increase in the future due to climate change.
- Heavy rain periods, especially during the winter, have become more frequent in northern Europe. This causes accelerated leaching of nutrients and suspended solids from bare land after harvesting. NBS structures, which have been developed according to the current climate, may exhaust their retention capacity in future. It is possible to find out the best NBS (water protection structure or forest management regime) in the future climate using a modelling approach.
- The increase in temperature, sea levels and frequency and magnitude of storm events reported across Europe in the last few decades have resulted in an increase of storm surge and coastal erosion, particularly due to the high impact of the wave energy closer to the coastal zones where cliffs or shorelines are composed of soils and/or soft rocks.
- Under climate change, droughts will also become more frequent and intense in the later 21st century in southern and western Europe, affecting human life, health and economy. The characteristics of drought phenomena are complicated as a result of non-linear physical links within the factors that trigger droughts, such as precipitation, evapotranspiration, soil moisture and stream flows. Therefore, research is needed into a multi-factor risk analysis of drought, past trends, future

projections, environmental exposure and NBS integration into drought policies and management plans adaptable to local, regional and national level. The key challenge is not only to design those mechanisms that will withstand droughts but to move to a proactive society that is resilient and adaptable to the drought risks. In this context, NBS are illustrated as a key to address these challenges.

- Today, conventional engineering solutions are accepted as viable and reliable measures for preventing slope failures or their consequences. However, the efficiency of these solutions must be evaluated in light of expected changes due to climate change. In many cases, a nature-based alternative may be a more sustainable and cost-effective solution. Nevertheless, if public safety is at risk, the most effective mitigation measure must be taken. In this regard, NBS for landslide mitigation still has to prove its feasibility.
- Adaptation mainstreaming is becoming increasingly relevant and is considered essential for policy development and practice of NBS. In current relevant frameworks, protocols, guidelines and policies, only 34% of the relevant policies directly refer to NBS, while most of the others (50%) only contain a weak to moderate reference. The remaining 17% do not refer to NBS at all. Most of the improvements, in terms of contribution towards mainstreaming and synergising of NBS, can be made in the documents and guidelines that already focus on HMR but do not yet refer to NBS as a way of reducing them.
- The notion and principles of NBS are action-oriented. In this regard, the concept of OAL serves as a benchmark for NBS upscaling, replication and exploitation in the policy-making process through building solid evidence based on their benefits in different climatic, environmental and socio-economic conditions. Planning, co-designing, operationalising, monitoring and evaluating NBS based on a novel concept of OALs can also alleviate the central challenges (e.g. political resistance, financial barriers, lack of collaboration, knowledge gaps) that hinder the successful implementation of NBS. Thus, OALs can serve as a bridge to facilitate the journey towards the successful linkages and synergies among science, policy and practice.
- Systematic mainstreaming of NBS could be produced by fostering co-creation processes across all sectors and levels connecting and harmonising adaptation aims, inspiring more effective use of manpower, diverse knowledge, and economic, social and cultural resources. Co-creation has a lot of potential for designing environmentally, economically, technically and socio-culturally sustainable NBS. To convince and foster the wider uptake of NBS, monitoring by field measurement and key performance indicators (KPI) are needed to demonstrate the multiple benefits NBS can provide in both short- and long-term.
- One of the most important ingredients of an objective assessment of a specific NBS is the availability and discoverability of NBS related data. To enhance discoverability and reduce data gaps in NBS data, it is essential to make them compliant to existing ISO standards related to metadata. One of the most effective ways to achieve this is to use catalogue services that adopt these standards. Development of NBS catalogue at a high standard and enriched by many attributes could enhance the transition between science, policy and practice.

Holistic management of HMR would require improved two-way mainstreaming of knowledge across policy silos and between research and practice communities. Further studies are needed to develop a global network of countries which can develop the NBS concept for building a better understanding of its performance against a range of multiple risks. There is a further requirement of developing co-creation processes and stakeholder engagement to support sustainable NBS by utilising a variety of skills, resources and place-sensitive approach. There is also a need to standardise the remote sensing/data monitoring and its accessible storage for future use in activities such as modelling of future climate, NBS and its efficiency. Furthermore, the basic concepts and the main technical elements of previous studies reviewed and presented here feeds into recommendations for developing synergies within current policy proceedings, scientific plans and practical deployment of NBS for HMR reduction in European rural and natural territories.

Declaration of competing interest

The authors declare no conflict of interest.

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Author contributions

PK conceptualised the idea, drafted the outline, wrote, edited and shaped the direction of the manuscript. SD and JS coordinated inputs from co-authors, who contributed to specialised topic areas and assisted in developing the draft. LSL assisted in shaping the manuscript. The author contributions to particular sections include: Introduction and Methods (PK, SD, JS), the HMH indicators, damages and their trends (PK, SD, JS, EB, NC, LU, TM, MR, AD), the potential NBS against HMHs including floods (AS, BB, FP, PK, SD, JS, AD, ET), droughts (NC, ML), landslides (TZ, MR, GG), coastal erosion and storm surges (SBM, LA) and nutrients and sediment loading (LU, LF), contents related to European and international policies for HMS and NBS (SJ, SD, PK, IP, JS), stakeholder engagement, expert interviews and the analysis and interpretation (KS, DP, MS, FB), plotting the figures (SD, JS, PK), NBS market opportunities (ASE, ALP), information on the upscaling and fostering of NBS (MARS, FGR), NBS cost-effectiveness and performance (PK, SD, JS, NC), monitoring NBS performance (SBM, PK, SD, JS) and barriers and data gaps for NBS deployment (LSL, SV, SDS). All authors contributed to conclusions, commented on the draft manuscript and assisted in the conceptual development of figures as well as the overall cohesiveness and proofreading of the paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.138855.

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